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TRAINING: AN OVERVIEW OF TRAINING
AND FLIGHT SIMULATOR TECHNOLOGY
WITH EMPHASIS ON ROTARY-WING
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An Overview of Training and Flight
Simulator Technology with Emphasis
on Rotary-Wing Requirements

Vertical Flight Training

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and Lloyd N. Popish

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Robert J. Randle, Jr.
and Lloyd N. Popish**

This book is dedicated to the memory of Robert J. Randle, Jr., who died 27 May 1995, virtually on the eve of the publication of this, his final work. Bob was our esteemed colleague and respected friend. We could say a great deal about him — about his many accomplishments, about his original contributions to his chosen field, about his dedication to the truth in his work, about the many attributes that distinguished him as a good and genuine man. But Bob wouldn't like that. We will miss him.

William E. Larsen
Lloyd N. Popish

But the eagle and the hummingbird are different.
Anon.

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FOREWORD

Flight training is a critical component of the aviation system. Operational efficiency and safety in any realm of aviation could not be successfully achieved in the absence of a practical method for selecting and training the people needed to operate aircraft. Without quality training even the best-designed and best-constructed aircraft is doomed to failure; and often, good training is called upon to compensate, at least partially, for less-than-optimal designs.

The present volume is a welcome addition to the voluminous literature on flight training. Although each of the topics discussed in the individual chapters of this compendium has been the subject of numerous papers, chapters, and in some cases, books, to my knowledge there has never been a treatise focusing specifically on training in the *vertical* flight world. The demands of this world *are* unique, a fact to which I can personally attest, and as such, deserve specialized attention.

As vertical flight assumes an increasingly important role in the aviation system, the importance of training for vertical flight is likewise increasing. The editors deserve commendation for recognizing these trends and for providing the vertical flight community with a valuable reference that will enhance the economy and safety of the world's air transportation system.

John K. Lauber
Member
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Washington, D.C.

ACKNOWLEDGMENTS

This document was prepared in response to a request from the Office of FAA Flight Standards, AFS-200. Its primary purpose is to address several of the important issues that were brought up at the NASA/FAA Helicopter Simulator Workshop (held at Santa Clara, California, in April 1992) and documented in the conference proceedings (DOT/FAA/RD-92/2, NASA CP-3156). The principal objectives of that workshop were (1) to clarify certain requirements for qualifying rotary-wing flight training simulators and (2) to establish a context within which a public preview could be conducted of what was at the time a draft version of Advisory Circular 120-63, "Helicopter Simulator Qualification" (11 Oct. 1994).

Given this background, we wish to express our appreciation to James I. McDaniel, Chief of the FAA's Vertical Flight Special Programs Office, ARD-30, whose office provided funds for these projects, and to Steve Fisher and Pete Hwoschinsky, of the same office, for their valuable guidance. The authorization and funding for these activities were carried on through Interagency Agreement DEFA01-88-Z-02015, between the FAA and NASA, dated 15 June 1988.

Our very special thanks are extended to our authors. They gave unstintingly of their time and expertise and did so without compensation and virtually without complaint throughout the usual run of editorial changes and production delays. We hope that our final product will in some small way reward them for their many efforts.

We wish also to thank Barry Scott, Chief of the FAA Technical Field Office at Moffett Field, California, and Dr. John Zuk, Advanced Tilt Rotor Technology Office, NASA, for their generous and helpful support in the realization of this work.

INTRODUCTION

The principal purpose of this publication is to provide a broad overview of the technology that is relevant to the design of aviation training systems and of the techniques applicable to the development, use, and evaluation of those systems. The issues addressed in our 11 chapters are, for the most part, those that would be expected to surface in any informed discussion of the major characterizing elements of aviation training systems. Indeed, many of the same facets of vertical-flight training discussed herein, were recognized and, to some extent, dealt with at the 1991 helicopter simulator workshop.¹ These generic topics are essential to a sound understanding of training and training systems, and they quite properly form the basis of any attempt to systematize the development and evaluation of more effective, more efficient, more productive, and more economical approaches to aircrew training.

Although there are many commonalities between fixed-wing and rotary-wing flight training, the remarkable versatility of rotary-wing aircraft, both in terms of their performance and the missions they fly, demands that we recognize the training requirements that are unique to vertical flight. The differences in the jobs that these two fundamentally distinct aircraft are designed to do must be addressed in the design and development of their respective training systems and programs, as well as in the regulatory criteria that are imposed on their pilot certification training and operation.

The vertical-flight and virtually unlimited maneuvering capabilities of helicopters and tilt-rotor and tilt-wing aircraft have opened up myriad commercial operations that have significant economic and social benefits. The well-ordered and widely used training systems for fixed-wing aircraft are not always applicable to rotary-wing operations, which are characterized by a large number of extensively distributed and marginally funded small operators. The unavailability of low-cost training media forces these operators, whether large or small, to depend mainly on their on-line aircraft for both revenue generation and training; as a result, the efficiency of both suffers. Beyond ab initio training, the aircraft is a poor training device; it is uneconomical, inefficient, and unsafe, and it is a poor place in which to learn and assimilate new material and to practice newly acquired skills.

The United States has always been the undisputed leader in aviation research, development, and production. Once again the vigor and high quality of these activities have placed us at the threshold of a new era and confronted us with new challenges in the continuing evolution and growth of our national aviation transportation system. That

¹ William E. Larsen; Robert J. Randle, Jr.; and Zuk, John: NASA/FAA Helicopter Simulator Workshop. NASA CP-3156 (DOT/FAA/RD-92/2), 1992.

system involves an already burgeoning commercial helicopter industry, and we may soon see the further expansion of vertical-flight commercial carriers with the introduction of the tilt-rotor, the civil version (CTR-22) of the V-22 Osprey, and possibly the tilt-wing aircraft.

Because of the proposed addition of vertiports for off-loading the runways used by the large carriers, these new vehicles have the potential to produce a profound effect on the infrastructure of the national airspace system. They will require new air-traffic control (ATC) procedures because of changes in the architecture and timing of traffic flow; and they may deeply affect the nature of current feeder-carrier operations, which of course do not have the spot-landing capability of rotary-wing aircraft. It is hoped that by anticipating rotary-wing operations our management of rotary-wing training and training equipment requirements will progress apace so that the transition from conventional fixed-wing requirements to the identification and fulfillment of those peculiar to rotary-wing training will be as expeditious as possible.

As mentioned above, the rotary-wing industry is made up of many, widely distributed small operators whose training needs and logistics differ markedly from those of the well-ordered, capital-intensive air-carrier training systems. The monolithic organization is rare in this fledgling industry, and that is a source of challenge to the training equipment community and to the federal agencies supporting and regulating aviation development. Rotary-wing training departments, equipment, courses, and instructors are not an integral part of corporate operations as they are and have been with the large air carriers.

In anticipation of the growth of the rotary-wing segment of the aviation industry, the Federal Aviation Administration (FAA) is in the process of proposing a new rule, NPRM, Part 142 (Title 14, CFR), which will authorize and regulate Certificated Training Centers. The objectives of this new rule are to increase simulator use, to eliminate the need for simulator exemptions, to standardize training, and to standardize the FAA oversight of trainers through a centralized, national training-program approval process. In an effort to maintain a broad perspective, the rule would not specify in any detail the differences between the use of fixed-wing and helicopter simulators. Instead, the FAA would issue certificates to qualifying training centers. The issuance of the certificate would be based on a set of training specifications, which could then be changed much more easily than the certification. Part 142 will either replace Part 141, Pilot Schools, or complement it, in which case Part 142 schools would cooperate with Part 141 schools in setting up mutually satisfactory arrangements for training students.

These new regulations can be a significant factor in addressing the training needs of the many small rotary-wing operators who have severely limited training budgets. In addition to providing for increased simulator use, however, more attention needs to be given to allowing more training and checking credit for the low-end (less complex) training devices. Also, in keeping with a heightened interest in simpler but more versatile

training systems, more attention should be given to the feasibility of using mobile training devices that can be quickly re-configured to accommodate the training needs for two or more aircraft types.

There are obvious similarities between the infrastructure of the current rotary-wing industry and that of deployed military rotary-wing units. As a result, the training capabilities envisioned by military commanders following the Desert Storm operation may hold equal promise for civilian rotary-wing operators. Highly placed military spokesmen, whose comments could well be harbingers of the future in civil rotary-wing training, called for portable and rugged training systems that could be taken into the field for on-site training to maintain and sharpen combat-readiness skills: "... deployable, fieldable systems are going to help the operating forces immeasurably"; increased emphasis on simulated training operations as the military goes through the downsizing brought about by the end of the Cold War; and the design and use of multiple-aircraft-type training simulators with short configuration-type turnaround times.²

One company was said to be "... working on a flexible mission rehearsal simulator in which a C-130 cockpit can be transformed into a helicopter cockpit in 30 minutes." Another is working "[On] an air crew training system for the Special Operations Forces that will enable them to train in seven different aircraft types" with database turnaround in 48 hours. Another example of training-device economy through simplification is the F-16 multi-task trainer (MTT), developed for the Air Force Reserve by Armstrong Laboratory (Williams AFB, Ariz.) that weighs only 1,500 pounds. It can be separated into two parts for easy transportation and can easily be rolled through a 66-inch-wide office door. It evolved from an earlier effort to develop an F-16 air intercept trainer (AIT) "to teach the pilot to play the piccolo" – meaning to teach him to operate the many radar and weapons controls that are on the stick and throttle. Although rudimentary, AIT still was required to give pilots a radar display and a small video display and to respond with good fidelity to the side-stick controller and throttle movements as the pilot maneuvered to attack enemy aircraft. The author of this comment also stated that "if the concept can be duplicated for other types of aircraft, there could be a very large market for MTTs." In particular, the Navy might be very much interested in having "flyable" simulators on board ships.

At the risk of oversimplification, it may be said that there are three overlapping performance domains represented by the activities of aircrew members: psychomotor activities in the guidance and control domain; serial and procedural cognitive activities in the management of aircraft systems; and cognitive, executive, decision-making activities in flight and resources management. These are all interactive with the need to maintain a veridical and ongoing "situational awareness." Failures in the cognitive activities of aircrew (human error) are generally conceded to be the major source of aviation incidents and accidents.

² Aviation Week & Space Technology, 25 Nov. and 16 and 23 Dec. 1991.

Indeed, the focus of human factors practitioners has changed over the years from human engineering and workplace layout to pilot-in-the-loop studies to the current intense interest in the "higher" aircrew intellectual functions. In a landmark paper, Weiner signaled the change of emphasis. Weiner said: "The human factors profession has long recognized the concept of design-induced errors. This paper simply extends the concept to a large-scale system, whose principal components are vehicles, traffic control, and terminals. These three components are embedded in two other components: regulations and weather."³

And, we would add, the growing need to fly by using automatic digital flight-control systems is a mixed blessing because these systems can both decrease and increase workload. It is obvious how they can decrease workload, but there is also a potential for increasing workload; it results mainly from a poor mating between the logic of digital devices and the logic of the human mind. By removing the pilots from direct involvement in actual aircraft control to a principally symbolic control, there is a danger of fragmenting the continuous situational awareness that is so essential to flight safety. The character of the critical training tasks is changing, and the much-discussed issue of training equipment fidelity is taking on new meaning. The new fidelity of interest is the one that pertains to the simulation of Weiner's "large-scale" system with its rich informational context and a flying task that is now more a deliberative than a motor process. Underlining this reality is the fact that procedural flight (intellectual) skills decay after only weeks of no practice, whereas motor skills are retained for months or even years (see Chapter 5, pp. 101-103). In line-oriented-flight training (LOFT) and in cockpit-resources management training (CRM) the emphasis is now on such factors as communication, flight strategies, crew coordination, task sharing, decision-making, and effective small-group problem solving. We must note that a similar sophistication of rotary-wing cockpits and automated flight-control systems cannot be far behind that of advanced fixed-wing systems. In consequence of this, the major training task becomes clear, and it differs significantly from that of a decade ago. In turn, that task determines training goals, means, and media.

The reader of the following chapters will learn of some novel ideas regarding the recognition of the uniqueness of rotary-wing operations. The authors never lose sight of the sharp differences that in so many important ways differentiate the rotary- and fixed-wing worlds. There is a challenge here for the regulatory agencies to support the rotary-wing industry in order to ensure that all operators have available to them training systems and equipment that are systematic, uniform, and cost-effective.

The regulatory mandates for rotary-wing pilot qualification and certification must recognize the significant differences between rotary- and fixed-wing requirements. And finally, but of primary importance, it must be possible to satisfy the qualification and

³ Weiner, Earl: Controlled Flight into Terrain Accidents: System-Induced Errors. Human Factors, vol. 19, no. 2, 1977.

certification requirements in more modest but functionally relevant training devices. Emphasis should be shifted from the traditional perception of simulator fidelity – with its primary focus on the preciseness with which the simulator duplicates the physical characteristics of the aircraft it mimics – to one of primary concern with the simulator's effectiveness as a teaching tool, that is, with how well it trains what it is purported to train.

The editors extend to the authors a hearty thanks for their contributions to this book. Their volunteering to work without compensation was inspiring and we deeply appreciate their taking time out from busy schedules to help in this effort. We hope they draw some small recompense from the fact that collectively they constitute an unprecedented source of expertise in the many interesting and challenging facets of rotary-wing training and operations.

We consider this publication to be a natural follow-on to the Santa Clara Workshop (referenced above) and mean for it to be responsive to the concerns expressed by the Workshop participants. We hope it will provide the information and motivation needed to begin planning the development of a systematic, economical, and universally accessible training system for the vertical-flight world. That should be next.

Federal Aviation Administration
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WILLIAM E. LARSEN
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1 AN OVERVIEW OF THE VERTICAL FLIGHT INDUSTRY: THE SOURCE OF TRAINING REQUIREMENTS

John D. McIntosh* and Lloyd N. Popish†

SUMMARY

The demand for rotary-wing flight training and training simulators has been flat and will remain so for several years. The primary reason is the current surplus of well-trained former military pilots who seek to be absorbed into the civil sector. The projected market for new helicopters throughout this decade also falls far short of the production seen in the 1980s; however, there is a growing trend toward more sales of light twins and intermediate class helicopters, the categories for which most simulators are sold. The expensive delays associated with the current air transportation system and the excessive costs of new airports or add-on runways can favorably affect the rotary-wing market segment. But rotary-wing vehicles must be brought into full participation in the public transportation business, which means that the public's perception of the safety, reliability, cost-effectiveness, and environmental compatibility of the rotary-wing vehicles must be improved. A critical factor in the future of rotary-wing training is the need for updated regulatory requirements that (1) recognize the differences between fixed-wing and rotary-wing training; (2) appropriately credit simulator and other ground training of rotary-wing pilots; and (3) recognize the inherent differences between air carriers and the rotary-wing flight industry in terms of demography, operations, and corporate structures and sizes.

INTRODUCTION

A review of the helicopter training industry should probably begin with a recognition of the fundamental differences that characterize and define the operations of fixed- and rotary-wing aircraft. For example, most fixed-wing pilots carry passengers as their principal business, most rotary-wing pilots do not; most fixed-wing pilots fly essentially routine missions in a single aircraft type, whereas rotary-wing pilots fly not only an awesome variety of specialty missions, but often do so in a variety of aircraft types; and virtually all professional fixed-wing pilots are instrument-flight-rules (IFR) rated, while on the contrary many helicopter pilots can work without the IFR rating because their missions are usually flown under visual flight rules (VFR) and at low altitudes.

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In addition to these pilot-function differences, it should be understood that a brief treatment of the helicopter flight training industry, in the context in which the term is employed here, will be, in essence, a reflection of the various market factors involved in the rotary-wing business, for when all is said and done it will be the number of rotary-wing aircraft, their distribution, and corporate size that will set the tone and scope of the pilot training programs. What follows is primarily a general discussion of the many variables and influences that can be expected to have significant effects on the rotary-wing training industry. It is not our purpose here to treat the subjects of training techniques and programs per se, with the exception that the role of training simulators is defined in terms of pertinent market and training factors.

Application of the advances made in training rotary-wing pilots has lagged the application of similar advances in the training of fixed-wing pilots. This lag is attributable in no small measure to the lack of regulatory upgrading of the means by which rotary-wing pilots can earn credits for training in equipment alternative to the aircraft itself. Because of the much greater effect of fixed-wing aircraft in terms of passenger volume and public safety considerations, this regulatory lag is to be expected. As a result, the use of advanced simulation training for rotary-wing pilots has fallen far behind that defined in FAR Part 121. This runs counter to evidence pointing to the training opportunities and enhancements possible with rotary-wing simulators, which in many instances exceed those offered by similar training of fixed-wing pilots.

Rotary-wing missions in general are more varied and in many respects more hazardous than their fixed-wing counterparts. They include, for example, sling-load operations, low-altitude flights over otherwise inaccessible terrain, flights to and from offshore drilling platforms, air-ambulance services, fire fighting, police work, photography and mapping, traffic reporting and control, news media activities, agriculture, executive transport, tours, taxis, charters, cargo, advertising, construction, training, and even the "fan drying" of rain-soaked athletic fields. Much of the pilot training these kinds of missions require — training that is expensive and potentially dangerous or impossible to conduct in an actual aircraft — can be accomplished safely, economically, and effectively in simulators. Moreover, difficult emergency procedures can be practiced quickly and repeatedly until pilot skills are upgraded to the desired level.

Fortunately, there is increasing official recognition of these training possibilities, and work is under way to confront and resolve the problems that stand in the way of more effective and appropriately accredited training of rotary-wing pilots. The training services and training equipment industries are working in conjunction with the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) to more effectively bring higher technology and performance standards to bear on the training of rotary-wing crewmen in the civil sector. The FAA has set up task forces and worked out plans whose goal it will be to bring rotary-wing simulation training on level with that of the scheduled airline pilots. "We are working toward the day when the term 'scheduled airline' includes [rotary-wing] flight as well." (ref. 1)

When the FAA published its first advisory circular for fixed-wing simulator qualification, it established standards that have saved millions of dollars, provided a basis

for vastly improved training, and created a model copied around the world and by our own military in some procurements. Extending that precedent to include rotary-wing aircraft is both desirable and possible, given the advances in rotary-wing simulation technology and the future demands that will be imposed on rotary-wing pilot training.

In addition to dealing with the special needs and problems associated with rotary-wing training, an overview of that industry must also consider the questions of supply and demand. For a variety of reasons, the business of rotary-wing operations, and therefore rotary-wing training, is not robust. In general, the number of helicopters produced in the United States has declined over the past decade, and for certain reasons, as mentioned above, there is a fairly long-term surplus of rotary-wing pilots. On the other hand, there are mitigating factors that are likely to favorably change the demand for rotary-wing flight services; they are discussed below.

It should be noted that much of the material presented here was derived from interviews conducted with major rotary-wing operators and manufacturers, from NASA studies, from interviews with industry providers of training services and equipment, and from trade journals and other published data on aircraft operating costs.

THE MARKET

Some statistical summaries at hand were examined in the interest of developing an indication of the makeup of U.S. civil rotary-wing operations. The summaries are based on data in the World Aviation Directory (ref. 2). Two hundred operators were listed, and within that group some 20 operational functions were identified. These included taxi/charter, construction, photography, patrol, training, medical, exploration, forestry/fire fighting, tours, news media, air carrier, agriculture, law enforcement, advertising, offshore, executive transport, cargo, and fan-drying of athletic fields.

The number of employees varies remarkably from operator to operator: from 1 to 2,267. Thirty-five percent of the companies had fewer than three employees; 20% had from three to six; 28% had from 7 to 19; and 17% had 20 or more. The median number of employees was nine and the mode was six. Forty-four percent of the operators had only one helicopter; 26% had two to three; 18% had four to seven; and 11% had eight or more. Forty-four equipment types were listed.

The Helicopter Association International (HAI) presented a survey and statistical analysis of questionnaire responses from 99 helicopter operators (ref. 3). The survey broke down all flight operations into three general categories: commercial, 61%; corporate flight departments, 29%; and public service, 10%.

Within both of the above breakdowns there is a great deal of duplication of operational functions across companies. A further way to categorize operations is by reference to the parts of Title 14 of the Code of Federal Regulations (CFRs) they operate under (commonly referred to as Federal Aviation Regulations or FARs). HAI's breakdown in these terms is as follows: Part 91, general operating and flight rules, 76.8%; Part 135, air taxi operators and commercial operators of small aircraft, 51.5%; Part 133, rotor-

craft external-load operations, 35.4%; Part 137, agricultural aircraft operations, 15.2%; public aircraft, 10.1%; Part 145, repair stations, 9.1%; and Part 121, certification and operations: domestic, flag, and supplemental air carriers and commercial operators of large aircraft, only 2%. The tabulated operators are fairly evenly distributed throughout the United States: 34% in the west, 25% in the south, 21% in the northeast, and 19% in the northcentral region.

These statistics characterize the helicopter operational world as a far-flung collection of small, independent businesses engaged in a highly varied repertoire of unique and socially beneficial tasks. The absence of large operators in this young industry presents a challenge to the training equipment designers and manufacturers and to governmental agencies supporting and regulating aviation development. For example, training departments, equipment, courses, and instructors are not integral with their corporate operations as they are and have been with the airlines. The small companies are dependent on training in their own or rented aircraft or on the purchase of training time from contract training schools.

The training, training equipment, logistics, and regulatory practices of the fixed-wing world are ill-suited to the support of this mosaic-like industry. New solutions are required that could easily encompass such radical innovations as mobile training units, multipurpose training devices with quick-change capabilities, new regulations adapted to new needs, enhanced approval of less complex and expensive simulators and training devices, and a general encouragement and support of decentralized training facilities and delivery systems.

The demand for rotary-wing pilots (and thus for training simulators) is, of course, a function of the demand for the kinds of services best provided by rotary-wing aircraft. That demand, in turn, is reflected in the demand for new aircraft, and in that respect the outlook is not encouraging.

Between 1973 and 1983, the U.S. production of civil rotary-wing aircraft averaged slightly more than 900 vehicles per year. In the last decade, that average production dropped by more than 50% — to about 435. It is true that during the most recent 10-year period, the number of rotary-wing aircraft imported into the United States, particularly from Canada and France, has increased. Nonetheless, most of the loss of U.S. production is attributable not to the increased competition but to cutbacks in corporate and government spending and to a slowdown in the growth of offshore oil drilling activities.

There are about 4,465 helipads in the United States, only about 180 of which are available for public use. The reason is that although most rotary-wing aircraft are used in public service, they are not used to transport the public. For example, about 2,000 of these helipads are used by local and state governments and by the federal government for purposes of law enforcement, emergency medical services, fire fighting, surveying, and terrain surveillance. About 890 of the helipads are in dedicated service to corporations (e.g., private transportation), and perhaps 450 of them are engaged in offshore drilling operations (ferrying personnel and supplies between offshore platforms and the coast). Another 450 are used in business applications — construction, passenger services, train-

ing, etc. Finally, about 220 are privately owned and used for such purposes as personal transportation and recreation.

There are a number of factors that will influence or determine the future demand for rotary-wing-aircraft pilot training and thus for rotary-wing simulators. But the primary one, of course, is the demand for civil rotary-wing aircraft themselves. For the period 1991-2000, total civil rotary-wing sales have been predicted to be of the order of 5,300, comprising four vehicle weight classes: light single (2,700), intermediate (1,345), light twin (1,135), and medium/heavy (120).

When the forecast figures are broken down by year, there is a conspicuous flatness in demand over the decade covered. There is, however, a slight trend toward the light twins (< 6,000 lb) and intermediates (6,000-15,000 lb). And, it should be noted, most of the training simulators built to date have been for these two categories of rotary-wing aircraft.

Given the forecast of 5,300 rotary-wing aircraft sales in the 1991-2000 decade, it is estimated that about one third will be delivered in the United States and that two thirds will be exported worldwide. The primary export markets will be the densely populated areas — Japan and the other Pacific Rim countries and Europe.

The market will also expand in Eastern Europe, but so will the supply side in those countries. Competition in the civil rotary-wing market can be expected from Russia and the other former Soviet states and from Eurocopter, a potential giant in the business compared with Aerospatiale and MBB, its founding partners.

Exclusive of the light-single helicopters that dominate the training and private-use segments of the marketplace, the rotary-wing market continues to be driven by the petroleum industry. The reason is simple: for that industry, the rotary-wing aircraft is an effective working tool that pays its way. Other segments of the market are in the areas of public service, emergency medical services, executive/corporate uses, and passenger services.

Sales of rotary-wing aircraft are now, as they have been historically, adversely affected by their poor public image — whether real or perceived, or, more likely, some combination of the two — that militates against their use as a practical means of general transportation.

Regarding rotary-wing aircraft in general, there exists a negative public image of their safety and reliability. Moreover, there are important environmental concerns, especially the noise problem, a lack of dependable IFR operations in icing conditions, and major economic (seat-mile costs) disadvantages. And air-traffic control systems — all of which were originally designed for fixed-wing aircraft — must be revised and conceived anew to accommodate a greater volume of IFR rotary-wing traffic at vertiport facilities.

It is going to be necessary to convince the public that the advantages and capabilities of rotary-wing flight can be expanded and exploited in a safe and environmentally

benign way before funds will be voted for vehicle purchases and facility construction. Obviously, the public is not going to accept — or will only reluctantly tolerate a limited version of — rotary-wing flight services that are excessively noisy or viewed as additional sources of air pollution. Reliability, both real and perceived, of the flight vehicles must also be improved. An emergency autorotation into a busy intersection will not do much for the public's image of rotary-wing aircraft.

When compared with regional fixed-wing seat-mile costs, rotary-wing aircraft are at a major disadvantage, with costs about double those of fixed-wing carriers. However, the tilt-wing and tilt-rotor vehicles promise to reduce those cost ratios from 2 to 1 to probably 1.2 or 1.4 to 1.

Investment capital, in general, is difficult to come by, and can be expected to remain so until debts are paid down and until the economy (in the United States and worldwide) picks up again. Still, if an investment can be shown to make economic sense, to ensure a fair return, and to be in the best interest of the country at large, the money will be forthcoming. Only thorough and effective planning combined with commensurate technical capability can ensure the future of rotary-wing aircraft.

Not only should we anticipate that investment capital for rotary-wing flight systems will be hard to come by, but there will be competition — in some instances keen competition — for whatever money is available. For example, the Boston-New York-Washington corridor is potentially one of the nation's major rotary-wing flight markets. But the competition there will be intense, with a multitude of alternatives, including reliever airports, runway additions, magnetic rail systems, and so-called bullet trains.

The potential market for rotary-wing flight services will be significantly and favorably affected by the congestion that plagues today's air transportation system. Airport delays equate to increased costs. For example, 21 U.S. airports now have annual delays of 20,000 hours or more. Those delays are estimated to cost \$5 billion a year. Predictions call for a total of 33 airports to have delays of this magnitude by 1997, 41 by 1998, and 50 by the year 2000.

Air travel projections for the year 2000 are for a 32% increase in jet transports and a 74% increase in the number of air passengers. Looked at in conjunction with the fact that about half of today's flight segments are less than 500 miles in length, one can see tremendous opportunities for a major rotary-wing or tilt-rotor flight role. Those opportunities will be even more pronounced in Europe and Japan than in the United States.

Alleviation of the current delay situation calls for expanded facilities. Adding a runway at an existing airport, even where such expansion is practical, costs about \$84 million in current dollars. That is enough money to build several helipads or vertiports and to buy some rotary-wing aircraft to use them. (An example of the latter possibility may indeed occur in crowded Japan.)

An industry team studying tilt-rotor missions for NASA reported that a new airport would cost between \$4 billion and \$8 billion. (The new Denver airport, originally

sold to the taxpayers as costing \$1.7 billion, will finally cost at least \$10 billion, and probably more, and, apparently, will not provide the problem solutions and service improvements promised.)

For half the cost of a new airport, NASA's study team reported, a network of 12 vertiports and 165 40-seat tilt-rotor aircraft could be built. (If the Denver airport is typical of actual new constructions costs, those numbers could be quadrupled.)

There are other promises of economic progress for rotary-wing flight, principal among which are cost models for a complete transportation scenario that factors in all trip costs, in time and money, from the "door of origin" to the "door of destination." This will come to pass when air-traffic control systems and facilities become further oriented to operations direct from city-center to city-center. Cost factors derived from this kind of model can be expected to yield cost comparisons that are far less unfavorable to rotary-wing flight operations, if not indeed favoring them.

Several factors are discernible that portend an upswing in the rotary-wing market. The export business is strong and is growing in densely populated regions throughout the world. Facilities for vertical-lift vehicles — a critical factor in future demand — are being expanded. New pads and vertiports are being built. The vertiport planned for downtown Dallas, it should be mentioned, will be able to handle the transitional rotary-wing vehicles — tilt-rotor, and tilt-wing — as well as helicopters. Conversely, the lack of such facilities in many parts of the world is going to constrain rotary-wing sales until appropriate support facilities are constructed.

If the newer tilt-wing and tilt-rotor vehicles are successful in penetrating the public sector of the passenger and cargo markets, and if the airspace regulations and infrastructure are developed properly and concurrently, then the demand, including helicopter demand, could amplify many times over. Regarding helicopters, the good work under way to reduce seat-mile costs and to improve reliability, perceived safety, and environmental compatibility must be continued.

TRAINING

The pilots of rotary-wing aircraft are a diverse lot whose skills vary over a much broader range than those of their fixed-wing brethren. They fly an array of vehicles, and the performance requirements for both vehicles and pilots vary according to the missions being flown. As a result, rotary-wing pilots require different and often unique kinds of training.

Between 70% and 80% of today's professional fixed- and rotary-wing pilots received their initial, and the major part of their subsequent, training in the military services, which is to say that the military was (and still is) the major source of commercial pilots (see Chap. 5). As mentioned earlier, there is today a glut of rotary-wing pilots, a result of force reductions and of a relatively stagnant economy in general.

But for some time the military services have been cutting back on the numbers of pilots in training. That, coupled with a higher retention rate by the military of its trained pilots, is going to cause the supply of military-trained pilots to contract to some extent. As that happens, the present oversupply of rotary-wing pilots will be absorbed — perhaps over the next 2-3 years. At that point it will be necessary for civil operators to take more responsibility for pilot training.

The career path for fixed-wing pilots follows a fairly standard and tightly controlled training regimen, one that always includes instrument training for IFR flight. In contrast, most of the flying done in conjunction with rotary-wing operations is done at low altitude and under VFR conditions. As a result, many rotary-wing pilots, neither forced by job requirements nor otherwise motivated, are not IFR rated.

This is changing, however. The trend in all of civil aviation, rotary-wing as well as fixed-wing, is toward more and more IFR equipment, systems, requirements, and training. Even for VFR flights, pilots are increasingly recognizing that IFR means more flight safety and enhanced mission capability. Undoubtedly, efforts made to upgrade the IFR skills of rotary-wing pilots will pay dividends over the long term in safer and more economic operations. And simulators are ideal tools for training IFR skills.

Modern cockpits are increasingly characterized by automatic flight-control systems and by computerized pilot-aircraft interfaces including sophisticated digital electronic displays and interfaces — the “glass cockpit.” These are not as highly developed in rotary-wing aircraft as they are in fixed-wing aircraft, but they certainly will be in the future. Coupled with this is the greater recognition of the role of crew cognitive performance in operational safety. Of the three major human performance domains on the flight deck — guidance and control, system management, and flight management — the last two are increasingly seen to be the major source of operational errors and accidents. Thus, the design and training goals now come from a need to keep the crew in the loop and thus prevent their role from changing from one of continuous, active participation to one of simply monitoring flight progress. Active participation is viewed as being essential to the creation and maintenance of a proper situational awareness. This will require a greater knowledge of human information-processing abilities and more effective design in the mating of human and engineering control logic. The emphasis is thus shifting from guidance and control, pilot-in-the-loop activities to that of the controller as communicator, decision-maker, and executive.

Engineering and dynamic simulator fidelity are not highly requisite for training in these cognitive skills. The relatively recent advent of cockpit resource management and line-oriented flight training was meant to provide learning opportunities for communications, decision-making, and “airmanship” in the use of crew resources. The exercise and honing of these capabilities is dependent not so much on simulation as it is on dissimulation, that is, pretending or playing the game in the interest of skill development and professional competency. Thus, the fidelity of interest in the near- and far-term will be that of environmental and operational fidelity in the creation of realistic, rich training scenarios. The training of intellectual performance does not require high physical fidelity; it requires comprehensive intellectual content and a full range of operational options.

In the meantime, however, and regardless of the mix between IFR and VFR training needs, the training of rotary-wing pilots will continue to employ aircraft, part-task training devices, and full flight simulators. But a major and characterizing difference between fixed-wing and rotary-wing training is that regulations, aircraft requirements, and perceived and actual costs still cause a far smaller proportion of rotary-wing pilots to profit from the training effectiveness and efficiency that full IFR simulators can provide.

To a great extent, the qualitative and quantitative differences that now exist between fixed-wing and rotary-wing training — with the advantage to fixed wing — derive from the FAA-induced inequalities relative to regulatory credits given for alternative (to the aircraft) advanced simulation training in FAA Part 121. But efforts are now under way to resolve some of these problems, and one result should be renewed interest in providing quality training to large groups of rotary-wing pilots who heretofore have been denied that opportunity.

It should also be noted that certain technical problems and deficiencies — for example, difficulties in modeling rotary-wing dynamics and our present inability to simulate binocular vision — limit the fidelity of rotary-wing training devices. For reasons such as this, affordable three-dimensional simulator visual systems could markedly affect the quality of simulator training of rotary-wing pilots.

The factors discussed in this chapter, as well as elsewhere in this volume, that affect the rotary-wing flight market will also create a continuing demand for training. Presently, trends are appearing that indicate that rotary-wing flight training will continue to move toward the full-service training companies. Some key people in the industry are expecting a substantial increase in the demand for simulator-based training in the 1995-1997 period.

Perhaps it is fitting to close this brief discussion of rotary-wing flight training with the following news item from the January 1994 issue of *Flying*.

Dave Givens, a Bell 412 pilot with Corporate Jets, became the first to complete FAR Part 135 check rides without using the actual helicopter. Givens completed all the requirements for pilot in command and instrument proficiency in FlightSafety's Bell 412 Level C simulator at the Fort Worth training center.

SIMULATORS

Today there are only a few civil helicopter simulators that would fall into classifications set forth in the draft copy of the FAA's Advisory Circular AC 120-63, Helicopter Simulator Qualification, which was written to implement qualification requirements for rotary-wing flight-training simulators. Those simulators are a Bell 222, Bell 212/412, Sikorsky S-6A, Sikorsky S-76B/A, Boeing Vertol 234, Aerospatiale 332L, and Sikorsky S-61N.

Attempting to forecast the number of simulators that will be sold in the present decade is an obviously difficult and tenuous business, given all the eventual determining market factors. Nevertheless, one can make a considered guess. Ours looks like the following.

Light singles and twins (< 6,000 lb)	4
Intermediate (6,000-15,000 lb)	3
Medium to heavy (>15,000 lb)	1
Tilt rotor	1
Tilt wing	1
Total	<u>10</u>

Whether there will be 10 simulator sales, or fewer or more, depends, again, on all the market forces previously mentioned, but perhaps most of all on the final form and implementation of the FAA's new rules for simulator qualification.

Simulator technology for fixed-wing and rotary-wing training is converging at the high end of the market in terms of the systems involved and the demands those systems make on training. For example, collision avoidance systems and flight management systems can be taught to fixed- and rotary-wing pilots using similar training environments and devices. But the rotary-wing pilot requires training in other procedures and techniques that are unique to the aircraft and missions he flies — search and rescue, emergency medical evacuations, and sling-load operations are a few examples.

It should be noted that flight and training standards for operations that are peculiar to the rotary-wing aircraft are now being addressed by training schools and by the FAA. Still, more remains to be done.

For purposes of comparing the costs of simulator and actual aircraft training, the following assumptions have been made: (1) a light twin helicopter for which the simulator cost is twice that of the aircraft; (2) 1,200 training hours spent in the aircraft, 3,500 in the simulator; and (3) a depreciation period of 10 years. (Note: crew pay and insurance are not included.)

The costs break down as follows. *Training in the aircraft costs \$605/hr*, consisting of the following per hour charges: depreciation, \$292; maintenance and parts, \$188; fuel and lubricants, \$100; and facilities/other, \$25. *Training in a simulator costs \$260/hr*, consisting of the following per hour charges: depreciation, \$200; maintenance and parts, \$30; facilities/other, \$27; and power, \$3. Moreover, these cost comparisons — \$605/hr for training in the aircraft, \$260/hr in the simulator — do not reflect the many less tangible but nonetheless real advantages of simulator training. For example, more of each training hour in the simulator can be devoted to actual training (e.g., there is no need to fly out to a particular location before training begins). And training can be provided in recovering from a wide range of abnormal and emergency situations, many of which would not be practical to attempt in the actual aircraft and many of which would be impossible to conduct in flight. As a result, the simulator-trained pilot may be far more capable of handling in-flight emergencies.

The widespread acceptance and utilization of simulator training for pilots of fixed-wing aircraft were functions of simulator fidelity, training cost reductions, and government regulations that allow credits for the training thus obtained. The same will hold true for rotary-wing flight training. The economy offered by simulator training of the pilots of rotary-wing aircraft has already been demonstrated, but much remains to be done in the areas of regulatory recognition and simulator fidelity.

High-fidelity and cost-effective training will continue to gain in importance in the rotary-wing market. But simulator fidelity, obviously, cannot be legislated into being. The right data must be modeled in the right way and implemented on equipment capable of executing the model and cues in real time.

Simulator fidelity is, at least in some important respects, more difficult to achieve for the rotary-wing vehicles than it is for fixed-wing aircraft. Involved are aircraft data and data collection, modeling techniques, visual and motion cues, and performance.

For example, rotary-wing dynamics are far more difficult to model for high-fidelity computer solutions. The flexibility of helicopter rotors and their continually changing angles of attack contribute to these problems. But engineers have developed substantially improved modeling techniques — blade-element rotor models are an example. The blade-element solutions are certainly an improvement over the alternative of generating a rotor-map-based design. Their use does require model-solution speeds that in the past were a problem, but that are now within the capabilities of the faster and less costly computers that are available.

Unfortunately, the problems that are peculiar to rotary-wing aircraft extend well beyond the rotor. Fuselage aerodynamic data are difficult to collect and document for slow forward airspeeds, in wind, and in hover. Engineers have to tune induced velocities, and there is a need for more data relevant to translational lift. And in the lower speed regimes more resolution is required — 32-bit, floating-point computers will be required.

Another technical challenge — and one that is considerably more difficult to deal with — concerns our inability to simulate binocular vision, given only two-dimensional, out-the-window visual displays. The problem is pointed up when a fixed-wing approach and landing is compared with that of a rotary-wing aircraft landing from hover.

For the fixed-wing simulator, the change in the pilot's perspective of the runway and its surroundings, at approach speeds of 100 knots or more, is sufficient to provide acceptable realism and pilot cues in the landing scene. But attempting to land a rotary-wing aircraft from hover or autorotation is another matter indeed. Now the pilot's perspective is changing very little, and the height cues are essential. As a result, he is almost totally dependent on depth perception in his efforts to determine his height above the surface. Although confined-area vertical cues help, the fidelity problem with the rotary-wing simulator remains to be solved.

The motion and visual cues needed in rotary-wing simulators are different from and more complicated than those needed in fixed-wing simulators. For example, the

field of view of the helicopter pilot is much greater than that of the fixed-wing pilot, particularly in regard to the important look-down angles the helicopter offers. Also important in helicopter training is the fidelity of the simulation of the onset and vibration cues.

Not many owners and operators of rotary-wing aircraft can afford to buy full flight simulators, which typically cost \$8 million to \$12 million. But specialty training companies and some educational institutions that serve a broad market segment will be able to justify the purchase of this training equipment and will be able to profit from it.

Based on projected deliveries of rotary-wing aircraft over the next 10 years (discussed in more detail elsewhere in this chapter) and taking into account the size and crew requirements of those helicopters and the customary ratios of flight vehicles to simulators, it can be estimated that 8-12 new, full flight simulators will be built during that period. That number could increase considerably if certain developments, which would have major effects on the use of helicopters and other rotary-wing aircraft, materialize.

For example, given changes that would admittedly be on a breakthrough scale, the public might be convinced to recognize and accept rotary-wing aircraft as vehicles that offer real advantages over airplanes and surface vehicles. The breakthroughs would involve changes in airway regulations that govern rotary-wing operations; improvements in the public perception of helicopter safety; noise abatement techniques for operations in city centers; construction of city-centered heliports and vertiports; and, probably, some commercial variant of the V-22 tilt rotor. And having said that, it must be added that although all of this speculation is practical, the likelihood of it being realized in, say, 10 years, is not high.

The training of helicopter pilots remains biased in favor of in-aircraft training and part-task devices for aircraft-type and familiarization training. There are very few certifiable full flight simulators, FlightSafety's 222, 212/412, and S-76 being among the better known examples of the very real advances that have been made in civil rotary-wing training. Many pilots and operators have already discovered the significant benefits to be derived from simulator training: expanded operational capabilities; improved safety, morale, and professionalism; and substantial reductions in training costs.

In summary, although simulator fidelity is a major factor, there are others. Fidelity itself concerns data and models, equipment technology, and training programs. Then there is the cost of simulator training, as well as training demand. It should always be borne in mind that a simulator, no matter how well designed, is still but a tool in a pilot-training program. The program itself must be designed to high quality standards and in such a way as to be cost effective.

CONCLUSION

This brief survey of the rotary-wing industry has pointed up four principal issues or problems — better perhaps, problem areas — that characterize the status of the business: (1)

economics, (2) quality of training, (3) supply and demand factors, and (4) public acceptance of rotary-wing aircraft for transportation.

1. Economics. The volume of rotary-wing pilot training is quite small relative to that for fixed-wing pilots. Moreover, there is less cost-benefit awareness associated with rotary-wing training than with fixed-wing training. At the present, the investments required to provide top-grade training for rotary-wing pilots is difficult to justify when there is, in effect, a glut of well-qualified pilots who received their training in the military. (This situation is expected to change, however, as fewer military-trained pilots enter the civilian market and as the existing surplus of pilots is used up.) Encouragingly, observable trends are toward better training, an expanding market for training, and increased awareness of the short- and long-term economic advantages of improved training equipment and techniques.

2. Training quality. The quality of simulator training of rotary-wing pilots is often tied into simulator fidelity. In recent years there have been marked improvements in simulator fidelity, but important issues still remain: data gathering, dynamic modeling, and visual scene simulation. All must be improved and are being improved, thanks to regulated training standards, competition in the training school industry, and the demands of owners, operators, and pilots.

3. Supply and demand. There is a surplus of helicopter pilots — not necessarily well-trained and current pilots, but a surplus nonetheless. Most of these pilots were trained in the military. But the number of pilots moving from the military into the pool of civil pilots is decreasing and can be expected to continue to do so over the next several years. As a result, the existing surplus of pilots will steadily decrease and a new demand for ab initio training will develop. In addition, leaders in the business are predicting a slow but steady growth in the sales of medium and intermediate helicopters. Concomitantly, the demand for IFR training will go up, which means there will be a need for more investment in full simulator training (see Chap. 4).

4. Public acceptance. Any radical changes in the magnitude of the demand for rotary-wing training will be contingent upon similar changes in the public's perception and acceptance of rotary-wing aircraft. If there is a breakthrough — if rotary-wing aircraft come to fulfill a major role in public transportation — then of course there will be a corollary and dramatic increase in the demand for facilities, vehicles, pilots, training, and simulators.

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2 TRAINING AND TRAINING SCHOOLS: MEETING CURRENT REQUIREMENTS

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SUMMARY

Rotary-wing operators differ organizationally, in the kinds of aircraft and missions they fly, and in the geographic and environmental conditions under which they operate. They have in common a general lack of training equipment and training capability, other than their own aircraft, and a keen and understandable interest in the cost of training. Simulator training is expensive, and although its near-term advantages are not always clear, the immediate outlay of money is. Only a few top-level, advanced simulators are available in the civil market, most of which are for a few types of large helicopters. Additionally, the Federal Aviation Administration (FAA) strictly limits the credits that rotary-wing pilots can earn in a simulator (unlike the situation for their fixed-wing counterparts). Lack of advanced simulators for rotary-wing aircraft, the cost of simulator training, the unavailability of regulatory credits for simulator training, and the virtual total reliance of the operators on in-flight training in their own aircraft (also expensive) are inducements for the operators to meet only the minimum FAA-specified training requirements and, therefore, to risk turning out minimally trained pilots.

INTRODUCTION

The rotary-wing industry comprises nearly 10,000 civil helicopters registered in the United States, and includes nearly 50 different helicopter models or series (ref. 1). Estimates of the number of these registered helicopters that are in use vary, but the active fleet has been estimated to be somewhat less — perhaps around 7,000 (ref. 2). There are approximately 36,500 active helicopter pilots — those having helicopter ratings and current medical certificates — in the United States. Training programs and related training circumstances vary widely for these pilots. They reflect the industry's diversity, the operators' varying different perceptions of the benefits of the various training activities, the large cost differences that characterize the training activities, and differences, of course, in the financial resources and the operational circumstances of the owners.

Only a few operators have integral training facilities and devices other than their own rotary-wing aircraft. Although a professional training center can provide flight training superior to that that can be accomplished in the aircraft itself, there are real and perceived barriers to widespread use of sophisticated rotary-wing flight simulators.

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The Federal Aviation Administration (FAA) severely limits the training credits that can be earned in rotary-wing flight simulators; those that are authorized are permitted primarily through regulatory exemption. At present, the sophisticated flight simulators that are available are for only a few of the helicopter types that are in service. Moreover, there is a significant and immediate direct cost to the operator for flight simulator training, as well as for related travel and per diem. Because most rotary-wing operators are, of course, cost-conscious, especially of near-term, direct training costs, many of them are induced to do only the minimum training required by the FAA or by third-party customers. Consequently, most flight training is done in the actual aircraft, rather than in sophisticated flight simulators, despite the superior training that can be accomplished in the simulators.

Cost considerations also affect the level of flight training accomplished in actual rotary-wing flight. In order to minimize flight and insurance costs, many rotary-wing operators and pilot training schools restrict their flight training to the minimum regulatory requirements, even though those requirements train pilots only to minimum standards. In short, FAA regulatory standards and rotary-wing operator cost considerations contribute to the reluctance of a major portion of the rotary-wing industry to embrace the superior training benefits afforded by formalized flight training programs utilizing advanced rotary-wing flight simulators.

TRAINING REQUIREMENTS

The basic training requirements for rotary-wing pilots are specified by the FAA in various parts of the Code of Federal Regulations (CFRs), Title 14, Aeronautics and Space. These CFRs are commonly referred to as Federal Aviation Regulations (FARs). For example, FAR Part 61, Certification: Pilots and Flight Instructors, specifies requirements that must be met in order to receive pilot certificates and ratings, as well as additional requirements for flight reviews, recent flight experience, second in command (SIC) qualifications, and pilot-in-command (PIC) proficiency checks for operations requiring more than one pilot (ref. 3).

Pilots operating under FAR Part 135, Air Taxi Operators and Commercial Operators of Small Aircraft, also must comply with the training and checking requirements specified in FAR Part 135 (ref. 4). Extensive guidance with respect to these training requirements for helicopter pilots operating under FAR Part 135 is found in the Air Transportation Operations Inspector's Handbook: "Each Part 135 certificate holder (with the exception of a Part 135 operator using a single pilot or only one pilot-in-command (PIC) in its operation) must obtain FAA approval of curriculums used for training flight crewmembers, instructors, check airmen, and aircraft dispatchers. The operator is responsible for ensuring that its training program is complete, current, and in compliance with regulations." (ref. 5)

Rotary-wing flight training comprises two broad areas. These depend on the pilot's experience in rotary-wing aircraft and the intended result of the training, once it is complete. Training within general areas may be further subdivided, in some cases into

substantial subparts. For purposes of explanation herein, these broad areas of rotary-wing flight training and their significant subparts are listed below.

1. Training that is designed and undertaken to qualify for a particular pilot certificate or rating. The principal subparts of this training category are initial rotary-wing pilot flight training for trainees who are not rotary-wing pilots; and follow-on training of previously trained rotary-wing pilots so they can obtain additional pilot certificate ratings.

2. Training of certificated rotary-wing pilots in order to satisfy specific regulatory or operational requirements. Included in this category are training for flight reviews and flight checks; to meet recent flight experience requirements; to comply with FAR operating part requirements, such as those of FAR Part 135; and operator-initiated, or what might be termed voluntary, training activities.

For both simulator-based and aircraft-based training, the content of the rotary-wing flight training programs depends on the following considerations:

1. Regulatory requirements and authorizations
2. Operator perception of training effectiveness
3. Operator assessment of operational requirements and risk
4. Operator financial considerations and perceptions of the economic effectiveness of particular training activities

Training for Pilot Certificate or Rating

FAR Part 61 specifies the requirements for issuing pilot and flight instructor certificates and ratings (including rotorcraft-helicopter ratings and instrument ratings), the operating conditions under which those certificates and ratings are necessary, and the privileges and limitations of those certificates and ratings.

Training related to these requirements must be given, with one exception, by a certified flight instructor: "[N]o person other than the holder of a flight instructor certificate issued by the Administrator with an appropriate rating on that certificate may (1) Give any of the flight instruction required to qualify for a solo flight, solo cross-country flight, or for the issue of a pilot or flight instructor certificate or rating; (2) Endorse a pilot logbook to show that he has given any flight instruction; or (3) Endorse a student pilot certificate or logbook for solo operating privileges" (ref. 3, sec. 3, p. 8)

The one exception to these FAR Part 61 requirements is the instruction given by an airline transport pilot to other pilots in air transportation service.

A certified flight instructor with a helicopter rating must have at least a commercial pilot certificate with a helicopter rating. The minimum required flight experience for a commercial pilot certificate with a helicopter class rating is 150 hours of flight time,

including 100 hours in powered aircraft and 50 hours in a helicopter. This is significant, for it means that a pilot with as few as 50 hours in helicopters and 50 hours in some other type of powered aircraft can be authorized to give flight instruction to student pilots in helicopters.

FAR Part 61.71 contains additional special rules for graduates of flying schools that are certificated under FAR Part 141 (ref. 6). These rules state that the graduate of a flying school certificated under FAR Part 141 is considered to meet the applicable aeronautical *experience* requirements for a pilot certificate if he applies for that certificate within 60 days of his graduation from that school. He is also considered to meet the applicable aeronautical *knowledge and skill* requirements if he applies within 90 days of graduation from an appropriate course given by a certified pilot school that is authorized to test applicants on aeronautical knowledge or skill, or both (ref. 3, sec. 71, p. 29).

Thus, training to qualify for pilot certificates, rotary-wing ratings, and instrument ratings can be accomplished on an individual basis by a certified flight instructor with appropriate authorizations, or through an appropriately authorized pilot school that is certificated under FAR Part 141 (see the subsection, Pilot Schools, further on in this chapter).

Training of Certificated Helicopter Pilots

For individuals who have pilot certificates with helicopter class ratings, there are certain training requirements that must be met if they are to remain active as pilots. Training of this kind varies widely in respect to frequency of the training, the areas covered by the training, and the extent of the training. This includes training undertaken to satisfy regulatory requirements for flight reviews and flight checks, regulatory requirements pertaining to recent pilot experience, training program requirements specified for commercial operations (such as in FAR Part 135, "Air Taxi Operators and Commercial Operators, 1992) and "volunteer" training programs developed by helicopter operators for their specific operations under FAR Part 91 (such as by corporate flight departments) (FAR Part 91, General Operating and Flight Rules).

FAR Part 61.56 requires that a pilot have completed a flight review within the past 24 months if he is to serve as pilot-in-command (PIC). There are limited exceptions, which include the following: A pilot who has "satisfactorily completed a pilot proficiency check conducted by the FAA, an approved pilot check airman, or a U.S. Armed Force, for a pilot certificate, rating, or operating privilege;" and "a person who has . . . satisfactorily completed one or more phases of an FAA-sponsored pilot proficiency award program."

Additional flight check requirements apply to pilots engaged in operations under FAR Part 135. The training to satisfy these requirements is known as the qualification curriculum segment of the operator's approved training program. It begins when formal training has been completed and ends when the pilot is fully qualified to perform without supervision and without restrictions in revenue service. These flight check re-

quirements have the following primary objectives: (1) to ensure that each flight crew member has reached an acceptable level of proficiency in all assigned duties before being released from training and supervision; and (2) to provide a means for measuring the effectiveness of the training program and for identifying and correcting training deficiencies (ref. 5).

The FAR states the following regarding aircraft-type qualification: "All pilots who are qualifying in an aircraft type are required by FAR Part 135.293 to complete a check in that type of aircraft before entering revenue service and annually thereafter The rule refers to this check as a competency check The rule does not specify the maneuvers (events) which must be accomplished on a competency check To ensure standardization and an adequate level of safety, the minimum acceptable content of competency checks for a FAR Part 135 curriculum is established by Order 8400.10. (ref. 5)

Pilots in command flying in operations under FAR Part 135 must also complete a Part 135 line check as required by FAR Part 135.299. The line check must consist of at least one route segment over a civil airway, an approved off-airway route, or a portion of either, including takeoffs and landings at one or more airports that are representative of the operator's type of operation. The FAA principal operations inspector (POI) may permit the line check to be conducted on the same flight during which the competency check is conducted (ref. 5).

For IFR operations authorized under FAR Part 135, a PIC must also have passed an instrument proficiency check within the previous 6 months.

Pilots who are required to complete recurrent training, competency checks, line checks, and instrument proficiency checks under FAR Part 135 are given an "eligibility period" in which to satisfactorily complete the checks. The eligibility period is 3 months, defined as the calendar month before the "training/checking month," "the training/checking month," and the calendar month after the "training/checking month."

FAR Part 61.57 requires that a pilot satisfy certain general flight experience and night flight experience requirements within the past 90 days if he is to serve as PIC. It further specifies instrument flight rules (IFR) experience requirements within the previous 6 months for a pilot who wishes to act as PIC under IFR. A pilot may act as PIC under IFR, however, if he has satisfactorily completed an instrument competency check in lieu of the IFR experience requirements. FAR Part 135.297 has similar requirements for pilots in command in FAR Part 135 operations.

Six major training program categories for FAR Part 135 operators are listed below.

1. *Initial new-hire training.* The initial new-hire training category is for personnel who have not had previous experience with the hiring operator (i.e., newly hired personnel). All such personnel must complete initial new-hire training.

2. *Initial equipment training.* The initial equipment-training category is for personnel who have been previously trained and qualified for a duty position by a given operator (not new-hires) and who are being reassigned to a different duty position on a different aircraft type, or to an aircraft of a category or class for which the crew member has not previously qualified with that operator.

3. *Transition training.* Transition training is for an employee who has been previously trained and qualified for a specific duty position by a given operator and who is being assigned to the same duty position on a different aircraft type.

4. *Upgrade training.* Upgrade training is for an employee who has been previously trained and qualified as second in command (SIC) by a given operator and who is being assigned as PIC to the same aircraft type for which he was previously trained and qualified.

5. *Recurrent training.* Recurrent training is for an employee who has been trained and qualified by a given operator, who will continue to serve in the same duty position and aircraft type, and who must receive recurrent training or checking within an appropriate eligibility period to maintain currency. All personnel must complete recurrent training for the duty position and aircraft type for which they are currently assigned within the appropriate eligibility period.

6. *Requalification training.* Requalification training is for an employee who has been trained and qualified by a given operator, but who has become unqualified to serve in a particular duty position or aircraft because of failure to receive recurrent training or a required flight or competency check within the appropriate eligibility period (ref. 6).

There are no regulatory training requirements specified under FAR Part 91. Training requirements that apply to these operators are those specified in FAR Part 61.

TRAINING REALITY

Of course, rotary-wing pilots and operators must comply with regulatory requirements pertaining to training and checking. According to helicopter pioneer Joe Mashman, the current U.S. training and certification requirements date back to 1946 when the first U.S. civil helicopter was certified. "At that time, three pilots — two of us from Bell's flight test staff and the government certification agency engineering test pilot — sat down and in 3 days established the training and certification requirements for this new type of aircraft. Developing these criteria was truly a guess in the dark, considering that no civil experience information and accident cause/factor data existed. The task was further complicated by an unclear picture of who would purchase the helicopter and how it would be used." (ref. 7)

Over the 49 years since those first training requirements were established, rotary-wing aircraft have become vastly more complex as have the operational demands of the wide variety of missions now flown by them. For example, many helicopters have two engines, two electrical systems, redundant hydraulic systems, and sophisticated and complex avionics systems. Helicopters now routinely fly IFR at speeds and altitudes they were incapable of when training and certification requirements were formulated in 1946. As a result, many in the rotary-wing industry maintain that training requirements have not kept pace with the advances that have been made in vertical-lift technology and its application, or with the attendant implications of increased demands on pilot capabilities and skills. "Comparison of the original pilot training and certification requirements to current ones shows that there have been no significant changes." (ref. 7)

The present regulatory training requirements establish basic, minimum requirements that must be met, but they allow pilots and operators to carry training beyond those requirements as they see appropriate. In actual practice, however, many pilots and operators neither accomplish additional flight training nor, if they do, use advanced training equipment, such as flight simulators. The risk related to these current training practices is, of course, that the practice of "training to minimum standards" produces exactly that — a pilot trained to the minimum standards.

Examples of areas in which the required training standards can be considered minimal include autorotation landings, instrument flight training, helicopter experience for flight instructors, flight reviews and competency checks, recurrent training requirements, and recent instrument experience.

1. *Autorotation landings.* Successful accomplishment of an autorotation to a touchdown is no longer required for a private pilot certificate, a commercial pilot certificate, or a rotary-wing airline transport pilot certificate. Flight proficiency requirements for the private pilot and commercial pilot certificates specify autorotational descents with a power recovery to a hover in single-engine helicopters, and do not reference autorotational descents in multi-engine helicopters. The Practical Test Requirements for a rotary-wing airline transport pilot certificate specify that autorotative landings in a single-engine helicopter "may be required" (ref. 3, Appendix B, p. 68). The usual argument against practicing autorotations is that current high engine reliability makes the risk of engine failure less than the risk of damaging the helicopter in autorotation training. The facts are that engine failures, as well as other malfunctions that require an autorotative response, do occur. Certainly, flight simulators are an ideal means of training for these emergencies in a risk-free environment.

2. *Instrument flight training.* For recreational or private pilot certificates, there are no requirements for instrument flight training, not even for inadvertent or unavoidable entry into instrument meteorological conditions (IMC). Here again, flight simulators are an ideal means for providing instrument flight training, including practice in appropriate emergency procedures.

3. *Helicopter experience for flight instructors.* It is possible for a pilot to become a certified flight instructor, authorized to give training in heli-

copters, with only minimal experience in helicopters. For example, a pilot with only 50 hours of helicopter flight time may apply for a commercial pilot certificate with a helicopter class rating, provided that other flight requirements have been met in other category aircraft, such as airplanes. If the pilot then passes the applicable required written and practical tests, he may be awarded a flight instructor certificate.

4. *Flight reviews and competency checks.* A helicopter pilot operating under FAR Part 91 need only have completed a flight review within the previous 24 months in order to act as PIC. If operating under FAR Part 135 and carrying passengers for hire, he need only have completed a competency check within the previous 12 months in order to act as PIC. This can, in fact, approach 13 months, depending on when in his eligibility period the pilot completed his previous check.

5. *Recurrent training requirements.* There are no recurrent training requirements for helicopter pilots operating under FAR Part 91. FAR Part 135 requires that pilots complete recurrent flight training each 12 months, but the annual FAR Part 135 competency check can be substituted for the required annual recurrent training. Pilots operating under FAR Part 133 (Rotorcraft External-Load Operations) need not undergo recurrent training if they have performed at least one rotary-wing external-load operation of the same class and in an aircraft of the same type within the previous 12 months.

6. *Recent instrument experience.* FAR Part 61 specifies instrument experience minimums of 6 hours of instrument time and six instrument approaches within the previous 6 months if a pilot is to act as PIC under IFR. These requirements can be satisfied, however, by having completed an instrument competency check within the preceding 6 months. In other words, in single-pilot operations, a pilot can take off with passengers aboard and immediately enter IMC, even if it has been 6 months since he had any instrument flight time.

Training Costs

Buying and operating rotary-wing aircraft requires a substantial financial commitment. Rotary-wing flight hours are expensive, whether for revenue-generating operations or for training. Since training flight hours rarely produce revenue or directly accomplish an operational mission, there is immense pressure within the rotary-wing industry to minimize training flight hours and their associated direct, immediate costs. A typical attitude in the industry is, "If it is not required by regulations or by my customer, I won't spend the money to do it." This attitude ignores both the long-term benefits of a comprehensive, structured training program and the long-term risks associated with the absence of such a program.

Pilot Schools

In order to be certificated under FAR Part 141, a pilot school must have FAA approval of a course outline for each training course it wishes to offer. There are additional requirements that must be met if the pilot school is to have examining authority. Once examining authority has been issued to a pilot school, that school may recommend graduates of its approved courses for pilot certificates and ratings without those individuals taking the FAA flight or written tests. (This does not apply to flight instructor certificates and airline transport pilot certificates and ratings.)

Minimum curricular requirements for helicopter pilot certification through a pilot school certificated under FAR Part 141 include the following:

Helicopter private pilot: (1) ground training of 35 hours; and (2) flight training of 35 hours, including 20 hours of flight instruction and 10 hours of solo practice.

Helicopter commercial pilot: (1) ground training of 65 hours; and (2) flight training of 150 hours including 50 hours of flight instruction and 100 hours of directed solo practice, at least 50 hours of which must have been in helicopters.

Helicopter instrument rating: (1) ground training of 35 hours; and (2) instrument flight training of 35 hours, up to 10 hours of which may be in a ground trainer that meets the requirements of FAR Part 141.41 (ref. 6, sec. 41).

At the ab initio and rating add-on levels, pilot schools train their students to meet regulatory requirements for a particular certificate or rating. There are great practical incentives for these schools to do all that they can to minimize risks while producing a reasonable return on investment. This minimizing of risk extends to training approaches, such as the omission of autorotations to a touchdown. There also is significant competitive pressure to achieve training objectives, such as qualifying for a pilot certificate with a helicopter rating, at the lowest possible cost to the customer. This competition is indicated by the large number of helicopter pilot schools competing for the limited number of students who can afford to participate in such programs. For example, Helicopter Association International (HAI) lists 74 certified helicopter pilot schools among its members (ref. 8).

FAR Part 91 Operators

There is a wide diversity of approaches to flight training among helicopter operators who operate under FAR Part 91. Some helicopter operations comply with the minimum FAR Part 61 requirements, such as the biennial flight review, recent flight experience, and instrument flight requirements, if applicable, and do no additional flight training.

There also are numerous helicopter operations under FAR Part 91 that go well beyond the basic FAR requirements. Some augment their basic training requirements with additional flight training in the aircraft. Others use flight simulators to augment

their training programs. Sometimes the flight simulators are used to provide recurrent training in specific pilot skills, such as IFR flight, even when the simulator does not match the actual aircraft being operated. For example, a pilot who flies an Agusta 109 helicopter, may go through an IFR recurrent-training syllabus in an S-76 flight simulator since there is no Agusta 109 simulator available. The reasoning is that the training received in IFR operations, procedures, and judgment is readily transferable to IFR operations in the Agusta 109.

At the upper end of the flight training range are those business aircraft operators who send their pilots through recurrent training twice a year using a full recurrent-training syllabus based on the use of sophisticated flight simulators. At the present, the only full-motion civil helicopter flight simulators in the United States are operated by FlightSafety International (FSI) at its training centers in West Palm Beach, Florida, and Fort Worth, Texas. Their training programs typically provide aircraft-specific training, as well as appropriate training in IFR operations, procedures, and judgment.

FAR Part 135 Operators

It is common practice among FAR Part 135 operators to accomplish only the minimum required flight training. This is best illustrated in the area of recurrent training, where the required annual competency check flights (FAR Part 135.293) and the required semiannual IFR check flights (FAR Part 135.297) can satisfy recurrent-training requirements for visual flight rules (VFR) operations and IFR operations, respectively. Operators may expand their ground training curriculum to include areas of attention such as aeronautical decision-making and cockpit resource management, because the cost and perceived risk associated with ground training are minimal compared with those of flight training. In flight training, which tends to be minimized, cost and perceived risk considerations are much more significant.

Of course, there are notable exceptions. One large helicopter operator, which has numerous satellite operations, chose to consolidate its training at company headquarters in the late 1970s. With more standardization, better facilities, and dedicated aircraft for training, it saw its accident rate drop from above five accidents per 100,000 flight hours to fewer than three per 100,000 flight hours. Further research by the same operator in the mid-1980s indicated that an inordinate number of its helicopter mishaps involved pilots in their first year of employment with the company. Consequently, the operator implemented a program in which company VFR pilots received recurrent ground and flight training after their first 6 months of employment (rather than at the end of 12 months) and then recurrent ground and flight training (consisting of the FAR Part 135.293 competency check) each 12 months thereafter. This policy further reduced the company's accident rate.

Another FAR Part 135 operator specializing in air ambulance service carries additional training significantly further through the use of full-motion flight simulators. This operator flies IFR-certificated helicopters for which there are no flight simulators in

the United States. Nevertheless, this operator includes annual flight training in the Sikorsky S-76 flight simulator, operated by FlightSafety International, as part of its training program. FSI and the operator developed a special training program in the FSI simulator to accommodate the operator's particular training needs.

Although the simulator cockpit and certain simulated aircraft responses are different from those of the actual aircraft flown by the operator's pilots, the operator considers the training in IFR procedures and decision-making to have valid transfer benefits, and to be valuable in enhancing safety. The operator cited two principal benefits of the flight simulator training program. First, the flight simulator training center has professional trainers whose full-time job is helicopter pilot training, uses curricula developed by professional trainers, and has extensive facilities and equipment dedicated to training. Second, the skills achieved in the flight simulator transfer very effectively to pilot performance in the company's aircraft, even though those are different from the simulator type used in the training. For example, IFR flight procedures and judgment requirements are basically the same in different aircraft types and in the simulator, even though the switches and their locations in the simulator may be different from those in the aircraft.

Simulator Consideration

There is a consensus among rotary-wing operators that simulators can offer significant training benefits for some operators, but beyond that point the consensus dissolves. One factor that limits simulator use is the small number of rotary-wing aircraft types for which sophisticated flight simulators are available. At present, civil motion-base simulators with visual systems are available only for a few large helicopters: the Bell 222, the Bell 412, and the Sikorsky S-76. Moreover, the immediate, direct cost of using simulators, also limits their use. For the rotary-wing operator, this cost includes not only the actual training cost, but the costs of travel to and from the training center, lodging, and lost productive time while the pilot is away.

Typical arguments against the use of simulators include, "We can train more realistically by actually flying our helicopter instead of [training in] a comparable simulator," or "There is no simulator that duplicates our specific helicopter, so why spend time on inapplicable training?" Both arguments are specious.

With respect to the first, it is foolhardy, and in some cases impossible, to attempt various maneuvers in flight that can be duplicated safely and with considerable fidelity in a simulator. Examples include anti-torque system failure, high-side engine-governor failures, engine failures during critical flight phases, and flight into icing conditions.

With respect to the second argument, that the simulator is not a duplicate of a specific helicopter, many decision-making and procedural responses to routine and emergency in-flight situations are essentially generic. As a result, the training applicable to these generic scenarios can be readily transferred to different helicopter types. Examples include inadvertent or unavoidable flight into instrument meteorological conditions (IMC), IFR procedures, and instrument approaches to minimums/below-minimums.

In reality, arguments such as those noted above mask the predominant cause of much of the resistance to the use of flight simulators in rotary-wing flight training — the significant actual cost of the training relative to the perceived benefits. In other words, training in flight simulators is considered by many to be impractically expensive relative to a readily *measurable* benefit, such as training and checking credits. As one operator stated, “Our [training] costs are already so high that the use of a simulator must help me reduce those costs, as well as provide that extra level of training Any simulator we use must be approved for credit toward the training that we do.” (ref. 9)

We see, then, that probably the two greatest obstacles to flight simulator use are (1) the regulatory limitations on check and training credits that can be earned in flight simulators, and (2) the cost of simulator training.

Check and Training Credits

The FAA specifies those training maneuvers and checks that can be accomplished in approved flight simulators. Although these credits for flight checks and training are clearly defined by the FAA for airplanes, the situation is considerably different for helicopters. “The helicopter simulator has no detailed regulatory basis, such as the airplane simulator has in Appendix H of Part 121. The operating and airman certification regulations do not have provisions for use of helicopter simulators that parallel those of airplane simulators.” (ref. 10)

In fact, the FARs note only two limited applications of simulators to helicopter pilot training:

1. FAR Part 61.57 permits the Administrator to authorize the conduct of part or all of the Instrument Competency Check in a pilot ground trainer equipped for instruments or in an aircraft simulator (ref. 3, sec. 57).
2. FAR Part 61.65 permits one half (20 hours) of the instrument time required for a helicopter instrument rating to be instrument instruction by an authorized instrument instructor in an acceptable instrument ground trainer (ref. 3, sec. 65).

The Air Transportation Operations Inspector’s Handbook lists those maneuvers and procedures in which PIC and SIC training must be accomplished for satisfactory completion of each category of helicopter flight training for FAR Part 135 operators. There are no maneuvers or procedures for which the Handbook currently authorizes the use of helicopter flight simulators. The Handbook states simply, “The criteria for the use of helicopter flight training devices and flight simulators are currently under development.” (ref. 3, sec. 65)

In other words, the FAA in its regulations and in the guidance it provides to its inspectors, currently authorizes only extremely limited training and checking credits for training conducted in rotary-wing flight simulators.

There are two exceptions, however, both of which are exemptions granted by the FAA to FSI.

Training Exemptions

Exemption 5324A was issued to FSI on 25 June 1993, replacing Exemption 5324. It expires on June 30, 1995. In granting the exemption, the FAA determined that a level of safety equivalent to that provided by the rules from which the exemption was sought could be achieved if certain conditions were met. The exemption states:

The FAA has indicated, on numerous occasions, its commitment to expand the use of simulators in training and flight testing of pilots as the state-of-the-art develops and as the public interest dictates. In this instance, the petitioner's request meets both criteria. Therefore, it is concluded that granting the requested privilege to the petitioner, within specific guidelines, would not adversely affect safety or the quality of flight training and testing performed.

Exemption 5324A permits FSI to use FAA-approved simulators in FAA-approved courses of training to meet certain FAR Part 61 training and testing requirements, provided that certain conditions are met. These FAR Part 61 training and testing requirements include the following.

SIC qualification

FAR Part 61.56: PIC [pilot in command] flight review

FAR Part 61.57: PIC recent-flight-experience

FAR Part 61.58: PIC proficiency check: Operations of aircraft requiring more than one pilot

FAR Part 61.65: Instrument rating requirements

Helicopter rating and type rating

Instrument flight instructor rating

Exemption 5241C was issued to FSI on 8 September 1993, and extends Exemption 5241B until 30 September 1995. Exemption 5241C permits FSI to offer contract pilot simulator training, instructors, and check airmen to holders of FAR Part 135 certificates, if certain conditions are met (ref. 12). For example, if the FSI training program is approved by the FAR Part 135 operator's POI for that operator, then the operator may receive FAR Part 135.293, initial and recurrent pilot testing requirements, and FAR Part 136.297, pilot in command instrument proficiency check requirements, in the approved FSI flight simulator.

CONCLUSIONS

The operating and management aspects of the civil rotary-wing flight industry vary widely. There are significant differences with respect to the number of aircraft operated, the number of employees, the experience levels of the pilots, the missions of the operators, rotary-wing aircraft types, operational environments, and operator financial resources.

There are also substantial variations in regulatory training requirements for rotary-wing operators, depending primarily on the CFR part under which flight operations are conducted, and on the characteristics of those operations. Regulatory training requirements can be considered minimal in several areas, for example, in the training of and practice in making autorotations, in instrument flight training requirements, and in the time intervals permitted between certain flight checks. Furthermore, there are no universally recognized standards with respect to rotary-wing flight training, such as there tends to be with the use of flight simulators in training pilots for the operation of airline-category fixed-wing aircraft.

The immediate, direct cost of training is a significant issue for the great majority of helicopter operators. Insurance costs limit the maneuvers that can be trained in the rotary-wing aircraft themselves, and many rotary-wing operators limit training flight hours to regulatory minimums because of the high cost of in-flight training. It is this high cost of training that provides many rotary-wing operators the incentive to do only the minimum training required by the FAA, or by third-party customers.

Although it is generally recognized that advanced flight simulators can provide superior training to that obtainable in actual rotary-wing flight, the credits that FAA regulations authorize for training and check rides accomplished in simulators are extremely limited. Therefore, the significant cost of flight simulator training (as well as travel and associated expenses) relative to the limited immediate training and check credits that can be earned, is a substantial barrier to their use. The use of flight simulators in structured training programs tends to be by corporate flight departments that are usually better able to afford such training than are the smaller operators.

The limited resources of rotary-wing operators does not permit the development of large, dedicated training programs, training staff, and training equipment. On the other hand, it is precisely these small operators who could derive the greatest benefits from using outside training organizations. Flight simulator use is also constrained by the severely limited number of rotary-wing aircraft types for which simulators are available. Currently, civil motion-base simulators with visual systems are available only for certain large helicopters: the Bell 222, the Bell 412, and the Sikorsky S-76.

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3 TRAINING SYSTEMS DESIGN AND DEVELOPMENT

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SUMMARY

A systematic approach to vertical flight training design and development is presented. The Interservice Procedures for Instructional Systems Development (IPISD) model is explained in detail. IPISD is supplemented with recent advances in learning theory and their applications to simulators and aircrew training.

INTRODUCTION

This chapter presents an overview of training system design and development and is intended to provide technical managers with guidance useful in planning and regulating civil training systems. It addresses a major concern of managers: whether the training of personnel is adequate to enable them to do the job for which they are trained. Training is, of course, essential to the safe and effective operation of helicopters and tilt-rotor and tilt-wing aircraft in the current and future national airspace. There is a problem, however: how to ensure adequate training without either overtraining or undertraining. The use of instructional systems development (ISD) is a means to resolve that problem.

ISD is the application of a systems approach to the training process. The key aspect of a systems approach to training is that all components of the instructional process are interrelated in predetermined ways. Each component has its own function and has an effect on other components. For this reason, each component must be considered both individually and in the way it interacts with other components. That is, the entire training system must be viewed as an interrelated whole.

ISD has grown out of basic research in three separate areas: (1) management sciences, (2) communication sciences, and (3) behavioral sciences. Contributions from management sciences include job analysis, occupational survey techniques, decision theory,

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cost-effectiveness models, and computer technology. Communications sciences have contributed by providing innovative use of electronics and media. Finally, the behavioral sciences have provided a solid foundation for the design of alternative approaches to instruction and to the measurement and evaluation of behavior.

It is our thesis that a systems approach to instruction is the most effective current means of evaluating, developing, and implementing alternative solutions to instructional problems. This can be done by determining instructional needs and priorities, developing effective and efficient means of achieving those needs, implementing solutions in a competent manner, and assessing the degree to which the output of the system meets the specified needs. ISD involves such a systematic approach. Following the ISD process it is possible to define training requirements, select training resources, prepare instructional lessons, train instructors, and produce pilots with the skills required to perform their jobs. Without such procedures, the risk of either omitting critical instructional material or including incorrect or unnecessary material is much greater.

Empirical evidence has shown that there are benefits to be derived from the proper use of the ISD approach. It greatly improves training in at least three distinct ways: (1) effectiveness, (2) efficiency, and (3) costs. First of all, training effectiveness is greatly increased through the design and development process, with a careful selection of what is to be trained, the measurement and evaluation of training, and the revision of the training program until it meets its objectives. Second, efficiency is greatly increased by offering effective instruction in a much more time-efficient way. Finally, although ISD does not always result in lower costs, the ISD process provides a systematic way of viewing the costs of training. There have been many demonstrations with combinations of effectiveness, time-efficiency, and cost considerations that have yielded impressive results on both large systems, with advanced simulators, and on smaller systems, which use no hardware at all. The common element has been the procedure and the approach, not the hardware or the equipment.

We view the Federal Aviation Administration's (FAA's) adoption of the Advanced Qualification Program (AQP) for fixed-wing aircraft as a major advancement in the training of aircrews. The ISD approach is an integral part of the AQP. The AQP is defined in AC 120-54 as "a systematically developed, maintained, and validated proficiency-based qualification and training alternative for personnel operating under FAR Parts 121 and 135 and for evaluators and instructors of recognized training centers" (ref. 1). An important change in the AQP is the adoption of a proficiency-based rather than a time-based training program. This focuses on the skills of the crew member and not just on the amount of time spent in classrooms and training devices. The AQP encourages the development and use of innovative training and qualification programs that incorporate advanced training technology, methods, and media. Pollock and Bender listed the

following advantages and benefits of the AQP: "(1) better trained and qualified personnel, (2) increased public safety, (3) human factors issues addressed, (4) increased safety by training flight crews, not just individuals, (5) training program effectiveness can be evaluated and revised if necessary, (6) time spent in training becomes quality time, (7) training programs can be structured to meet specific needs, and (8) full advantage of simulators and other training devices." (ref. 2)

Many major airlines are working to have their training programs approved by the FAA under the AQP. However, we still find many flight training programs that are not precisely defined and that are based solely on the professional judgment of the flight instructors who deliver the programs. These instructors are typically subject-matter experts with very little knowledge of the instructional and learning processes and of the appropriate use of media such as simulators and computer-based instruction. There is a need for precision in training programs. This was pointed out in the Kemeny report on the accident at Three Mile Island, which stated that the content of the training provided to control-room operators was imprecise, that it was not based on detailed and systematic analysis of the operator's tasks, and that available training-program development technology had not been employed (ref. 3).

Caro states:

Operators of imprecisely defined aircrew training programs cannot demonstrate the relevance and adequacy of their course content with respect to known training requirements and, therefore, might be judged culpable in the event of errors committed by aircrews they trained. These operators would be hard pressed to build a legal defense against a charge that their training is inappropriate, should they be required to do so. Because procedures do exist whereby the necessary precision in defining training-program content can be obtained, as the Kemeny Commission noted, it would be difficult to defend the adequacy of a training program that is not derived through those procedures. These operators also face a technical problem. Imprecisely defined training programs cannot be packaged for efficient delivery, cannot be made available economically to small groups or individual pilots when needed, and cannot be controlled easily or standardized from one administration to another. [ref. 4]

A MODEL FOR INSTRUCTIONAL SYSTEMS DEVELOPMENT

The systematic model that we are drawing heavily on is the Interservice Procedures for Instructional Systems Development (IPISD) that was prepared for the U.S. Armed Forces by Branson and his colleagues at Florida State University (ref. 5). IPISD is a systems

approach to making a rational selection of valid training content, materials, strategy, and media to meet job-performance requirements. It illustrates the rationale for the selection of the full context within which the training is to take place. These detailed systematic procedures provide for precision in training programs.

IPISD is a five-phase model. It describes the functions necessary to *analyze* instructional needs; to *design*, *develop*, and *implement* instruction; and to maintain *quality control* of instruction. A sequential relationship of these functions is recommended. These five phases — analyze, design, develop, implement, and control — are discussed below (from ref. 6).

PHASE 1: ANALYZE

The *analyze* phase presents procedures for defining what the jobs are. The inputs, processes, and outputs of this phase are all based on job information. During the analyze phase, an inventory of job tasks is compiled and divided into two groups: tasks not selected for instruction and tasks selected for instruction. Performance standards for the tasks selected for instruction are determined through interviews or observations at the job site and are verified by subject-matter experts. The analysis of existing instructional material is done to determine if all or portions of the analysis phase and other phases have already been done by someone else following the ISD guidelines. As a final step, the list of tasks selected for instruction is analyzed to determine the most suitable instructional setting for each task. There are five specific outcomes of this phase: a list of job tasks, a list of training tasks, job performance measures, analysis, and selection of the instructional setting.

List of Job Tasks

The procedures used in developing the list of tasks needed to perform a particular job include finding out exactly what people do when they do that job, the order in which they do it, the conditions under which they must do it, and the level of skill or performance deemed adequate for the job. This effort probably represents the greatest investment of time and money of any of the initial steps in training development. This investment, when it is properly managed, yields extremely impressive payoffs, principally because of its effect on the organization of training and because it focuses attention on the important aspects of the job.

List of Training Tasks

Selection of the tasks to be trained is a critical step in the process because it is at this point that decisions are made that will obligate resources throughout the entire process. Prior-

ties must be assigned to the various tasks, since there is rarely enough time or resources to train everything that it might be desirable to train. Among the criteria that have been used in the past for selecting the tasks are the following:

- Percentage of people who actually have performed the task
- Percentage of total work time spent on the task
- Probable consequence of inadequate performance
- Task delay tolerance
- Frequency of performance
- Task learning difficulty
- Probability of deficient performance
- Immediacy of task performance

Job Performance Measures

The development of job performance measures (JPM's) for each task selected for instruction must be of the highest possible technical quality. It is in this step that a clear statement is made about what is expected in job performance. JPMs measure that which is desired by the incumbents. The development of JPMs is a difficult technical assignment, primarily because of problems with the following: (1) validity, the degree to which a JPM measures what it is intended to measure; (2) fidelity, the degree of similarity between the training situation and the operational situation that is simulated; (3) administration of JPMs, for there can be some complex problems of logistics; for example, in some instances there will be test problems involving the use of heavy, complicated, or delicate equipment which may or may not be continuously available; (4) costs involved in obtaining high validity and fidelity may exceed the probable benefits; and (5) the time necessary to administer some tests is longer than what is practical under normal circumstances.

Each JPM is associated with one task, and it measures enough parts of that task to make possible a sound generalization about task performance. In some instances, the whole task must be measured in order to make a judgment, whereas in other instances certain parts of the task may be sufficient to reveal the incumbent's ability to perform. The final step in the development of JPMs is their validation under field conditions.

Analysis

A basic objective of this step — the analysis of the job analysis, task selections, and job performance measures — is to facilitate and encourage training in all those situations that

meet the established criteria. Thus, a careful analysis of the existing instructional materials should be conducted. The IPISD procedures provide guidelines for making the analysis and suggest criteria that can be applied in order to estimate the potential usefulness of existing training.

Instructional Setting

Selection of the instructional setting for the tasks selected for instruction is very important in arranging the training so that it will be available to the trainee when the information or skills to be trained are needed by the trainee. There are five instructional settings in the ISD procedures to which tasks can be assigned: (1) job performance aids (JPAs), which can range from simple lists of instruction to step-by-step procedures for task performance; (2) self-teaching exportable packages (STEPs), which can be in print form, in audiovisual form, or in the form of a kit that can be assembled or manipulated; (3) formal on-the-job training (FOJT) where the facilities are adequate; (4) installation support schools (ISSs), principally to meet local needs; and (5) resident schools (RS) instruction.

PHASE 2: DESIGN

The *design* phase is concerned with designing instruction using the job analysis information from Phase 1. The first step is the conversion of each task selected for training into a terminal learning objective. Each terminal learning objective is then analyzed to determine the steps necessary for its mastery. Test items are designed to match the learning objectives, and a sample of students is tested to ensure that their entry behaviors match the level of learning analysis. Finally, a sequence of instruction is designed for the learning objectives. There are four specific outcomes of this phase: learning objectives and analyses, test items, test of trainee entry behavior, and task sequencing. These outcomes are discussed below.

Learning Objectives and Analyses

Learning objectives have been found to be an extremely effective means for controlling the *intent* of instruction. Learning objectives must be stated in terms of what the student is expected to do rather than in terms of what the instructor or supervisor is expected to do; that is, learning objectives must be based directly on the job performance measures. Because there is a direct relationship between each learning objective and a job performance measure, or part of a job performance measure, much unnecessary instruction can be eliminated. The description of learning objectives should have, at least, (1) a verb which describes the observable action, that is, the kind of behavior that will be accepted as evidence that the objective has been achieved; (2) a statement of the conditions under

which the behavior is expected to occur; and (3) a statement of the standard by which the performance is judged or evaluated.

Test Items

The key to any successful instructional program is the precision with which what is taught is tested. The quality of the tests developed in this phase of the IPISD model will have an important effect on the quality of the instruction. The tests must have good technical characteristics (reliability and validity) since they will form the basis of many decisions that will be made about students and about the quality of the instruction. Managers need also to be concerned with the degree of fidelity that is available in the testing situation, the completeness and thoroughness of the tests, and the use of these tests in establishing the baseline (cutoff scores). Since instruction is not offered for its own sake, but as a means to an end, the test items used must be consistent with the overall aims of the instructional program.

Trainee Entry Behavior

Adequate design of ISD training requires a careful analysis and description of the entry behavior of the trainee as it relates to the proposed training program. Entry behavior falls into two principal classes: (1) basic aptitude and ability, and (2) acquired knowledge and skills. In the short term, very little can be done to change the basic aptitudes and ability of the entering trainee. However, longer-term results can suggest the need for different selection criteria. Assumptions must be made about the knowledge and skill levels of the trainee and then verified or adjusted depending on the results of the testing of entry skills. In addition to the entry test, which is used to adjust the beginning point of a course, pretests for the instructional unit are developed to see to what extent students have already mastered the skills to be taught. Provisions can be made for students to bypass certain blocks of instruction if the pretests show that they already meet the desired skill levels.

Task Sequencing

The specific purpose of task sequencing is to identify the learning objectives that are independent of each other, those that are dependent on others, and those that may have supportive relationships. When two learning objectives are independent, the learning of one has no effect on the learning of the other. When two learning objectives are dependent, it is necessary to learn one before learning the other; that is, accomplishing the latter learning objective is dependent on the learning that occurred in achieving the first learning objective. The third possibility exists when the achievement of one learning objective

supports or facilitates the learning of another, but in which the order in which they are learned is not important; that is, the learning in one will transfer to the other no matter which one is learned first. Organizing the learning objectives into these three categories will assist the developers of instruction in two ways: (1) it will identify the proper sequence of learning objectives, and (2) it will provide maximum flexibility when the relationships are supportive or independent.

PHASE 3: DEVELOP

In the *develop* phase, instructional materials are prepared. Readers should refer to the later section in this chapter on Learning Theory and its Application to Flight Training. The develop phase begins with the classification of learning objectives by the learning category that is necessary for optimum learning to take place. It is followed by a media-selection process to determine how the instructional material is to be packaged and presented to the student, and instructional management plans are developed to allocate and manage all resources for conducting the training program. Instructional materials are then selected or developed and tried out. When materials have been validated on the basis of empirical data obtained from groups of typical students, the training program is ready for implementation. The five specific outcomes of this phase are classification of learning objectives, media selection, analysis of instruction, development of instructional materials, and validation of instructional materials.

Classification of Learning Objectives

Specific learning events or activities must occur in the instructional environment in order to produce the desired learning outcomes. We recommend the use of Gagné's learning hierarchy in the development of learning objectives for flight training.

Media Selection and Instructional Management

Media selection is a major means for determining how the training materials are to be presented to the student. The choice of media influences both the effectiveness and cost of training. Because a systematic approach to media selection requires consideration of the nature of the learning objectives and the type of learning, the instructional manager must be aware of the list of media mixes or alternatives being considered and must be able to contribute to the decision-making process by providing information about facilities, personnel, and other resource availability. A number of matrices have been developed that assist in the selection of media. Reiser and Gagné discuss this issue in detail (ref. 7). Also, many computer-based media-selection systems have been used on major training development projects, and many of these systems have specified the use of simulators

of various degrees of fidelity in aviation-based training programs. When two or more media can satisfy the learning objective, the decision can be made on the basis of cost, availability, or other factors. Once the media have been selected, the management plan can be specified.

The management plan is the principal organizational document for the training. It indicates exactly how the training is to be conducted, how the students are to be managed, when and where they will be tested, what the instructors and other support personnel are to do, and how each of the many elements within the plan work together. The management plan is also used by the internal evaluator to plan and conduct the internal evaluation. It is usually necessary to develop the plan with the assistance and cooperation of the internal evaluator in order to be sure that what is being planned can be properly evaluated. The plan can be usefully divided into two general categories: those areas employing the group block-scheduling mode and those using self-paced modes. With the increased use of instructional delivery techniques, it is no longer an absolute necessity to use an instructor solely in a talking or demonstrating mode. The job of the instructor has increased in complexity to the point where the instructor is more often thought of as a manager of instructional resources. This may mean special preparation or training and possible assignment of part of the instructional staff to provide the necessary support for the instructor in the managerial role.

Analysis of Instruction

A review of existing instructional materials must be conducted for the purpose of determining their potential value for use in the training program under consideration. These materials are reviewed specifically to see whether they meet the learning objectives established for the training program that is being developed, and to determine whether they can be used or adapted for use within the context of the selected learning guidelines and media. Materials are selected or adapted for use where they are appropriate, and are rejected when they fail to meet the current program needs.

Development of Instructional Materials

One of the larger efforts in the ISD process is that of developing instructional materials to accomplish the learning objectives, and this is the appropriate place to produce them. The process includes developing draft materials, trying them on students, and finally sending the materials to appropriate production specialists for development. A variety of approaches are available for use, such as lectures, video tapes, slide/tape presentations, job-performance aids, and formal on-the-job training. As previously indicated, the appropriate mix of these approaches will depend in large part on the available time, facilities, and resources.

All ISD training is developed according to a common systematic approach. Fundamental to the process is the development of the minimum instructional content necessary to accomplish the intended learning objectives. To achieve this, a "lean" approach to writing initial drafts is required. Trade-offs must be made between the ideal way of approaching the training and the resources available. As the instructional materials are tried out with students, weaknesses and discrepancies can be identified, and, where necessary, materials can be expanded or revised to overcome any detected shortcomings. The inputs to the development of instructional materials will be all of the documentation available from the processes thus far. Any or all of these inputs may be required in correctly applying the process.

Probably the most difficult area for management in developing instruction is that of coordinating the efforts of a variety of people in a number of different skill areas. Depending on the media and method selected, the manager may be required to arrange for the production of video tapes, printed materials, audio materials, the development of training aids or devices, and any one of a number of other instructional aids and devices. In many instances, it will be necessary for the manager to challenge earlier decisions, perhaps because of a lack of facilities or resources, because of the waiting time required to have materials produced, or because of revision redevelopment decisions necessitated by test results. Further, the manager may encounter difficulties when trying to get production personnel to produce materials according to the current program needs defined by ISD processes rather than according to techniques and procedures they have used previously. It is not uncommon for media specialists to be more concerned with the appearance and style of the production than with its instructional effectiveness. Thus, the manager must constantly be aware of the instructional requirements of the materials as opposed to their cosmetic appeal. Of course, all developed materials must be consistent and accurate in content.

Validation of Instructional Materials

The heart of the development phase is the validation of instructional materials. The validation process is probably the most powerful procedure in the entire development effort. If the learning materials selected and developed have been produced efficiently, they will have the minimum possible elaboration, and when tried on students for the first time, some shortcomings are to be expected. These inadequacies can be corrected through the process of revision.

It is important that the students used in the materials-validation process be truly representative of those for whom the instruction is being designed. Only a few members of the target student population should go through the materials at first, and revisions should be made on the basis of those first trials. Following this initial revision, the number of students using the materials is increased in order to detect any other errors. Finally, when the instructional materials are thought to be complete, they are tested on enough

students so that their effectiveness can be demonstrated at an acceptable level of confidence. As the materials are improved, fewer and fewer students will have difficulties with them, and more and more students will work through them to an acceptable level of performance. At this point, the training is ready for introduction into the setting for which it was designed.

The ISD process requires that all test items relate directly to the instructional objectives. Because of this, the test results can be used not only to determine if the student has passed, but also to determine which of the instructional areas seem to be causing the most problems. The same data that were originally used only to evaluate the students can now be used in an equally successful way to evaluate the instruction. Analysis of these data will clearly point out those areas of the training that require revision. An extremely important management function of this phase is that of ensuring that the revisions made are necessary, and that the data have been carefully analyzed and interpreted before these revisions are made. Managers must also be concerned with ensuring that the instruction developed meets minimum requirements commensurate with available training resources.

PHASE 4: IMPLEMENT

The *implement* phase refers to the steps necessary to implement the instruction. Staff training is required for the implementation of the instructional management plan and the training, and some key personnel must be trained to be managers in the specified management plan. The instructional staff must be trained to conduct the training and to collect evaluative data on all of the instructional components. At the completion of each instructional cycle, management staff should be able to use the collected information to improve the instructional system. The specific outcomes of this phase are (1) information on student and training resources and (2) a completed cycle of instruction.

Student and Training Resources

At this point in the process, the instructional portion of the management plan, which was developed previously, is ready for implementation. The implementation of the management plan is the terminal step in the planning and preparation and takes place just before regular training begins. Instructional management plans will vary considerably, ranging from those involving resident school instruction to those involving formal on-the-job training programs. No single plan will serve all purposes. It is at this point in the process that any discrepancies or deficiencies in what has gone before will be identified and corrected before the students begin the training.

The first thing that must be done is to make a complete inventory and checklist to be sure that everything necessary for the implementation of instruction is available. If necessary, changes, additions, and deletions should be made to the instructors' manuals and students' manuals to ensure that they are completely up to date. What the instructors are supposed to do and when they are supposed to do it must be made absolutely clear, and any specific or unique requirements that they may be required to meet must be defined. And if necessary, the student manuals, all necessary exercises, training, directions, and other requirements should be completed or modified.

The next step is to identify those instructors who are going to be involved in the implementation effort and to provide whatever additional training may be necessary for them to carry out the instructional plan. Most often, this involves rehearsal and review of the uses and functions of the equipment to be used, practicing demonstrations, or rehearsing test administration when tests have unique features.

Finally, the procedures become administrative in nature. Time, space, necessary facilities, and equipment must be secured and checked. When this has been completed, instruction is ready to begin. There is often a frenzy of activity just before the deadline. The manager will ordinarily find himself heavily involved in a wide variety of decisions that must be made and executed before the students arrive. Planning for every possible contingency might require more time than is required for simply managing and solving last-minute problems. Many of the problems to be solved at this point will have relatively straightforward solutions. The manager should expect to be constantly available to those who need him during those weeks and days just before the implementation of the new instruction. Timely decisions at this point can have a dramatic effect on meeting the deadline.

Completed Cycle of Instruction

A completed cycle of instruction is the first of four continuing steps in the ISD process; the others are internal evaluation, external evaluation, and system revision. These four functions occur continually so long as there is a need for training.

Obviously, the role of the instructor is vital. As the instructor is provided with more and more resources and is trained in their use, his role increases beyond that of traditional classroom lectures to include the duties of instructional manager. In self-paced, peer-tutored, computer-assisted, and other nontraditional forms of instruction, the role of the instructor will be even more vital to the attainment of the training objectives. The instructor will manage resources, make presentations, administer tests to students, record data, and make recommendations for improvements to the training. Working in cooperation with the internal evaluation group, the instructor will help evaluate the students and the training.

The manager needs to be concerned not only with the administrative requirement of making sure that all the instructors perform as expected, but will often find his role expanded to include the following:

1. Counseling and reassuring instructors who are unfamiliar and uncomfortable with new instructional techniques
2. Providing encouragement and support to those instructors who continue the efforts as planned until sufficient data can be collected in order to make reasonable revision decisions
3. Meeting regularly with the internal evaluation group to coordinate data so that evaluations can be completed and revision decisions can be made
4. Ensuring that there are sufficient learning materials and resources available, and that there is adequate time to complete the instruction as planned
5. Managing the personnel and physical resources, with constant attention to ways in which resources and facilities can be conserved and personnel can be freed from more routine duties to make their time available for other necessary ISD functions

PHASE 5: CONTROL

The *control* phase is concerned with the procedures and techniques for maintaining instructional quality control. Evaluation and revision of the training program are carried out by personnel who preferably are neither the instructional designers nor the managers of the course under study. The first activity (internal evaluation) is the analysis of learner performance to determine instances of deficient or irrelevant training. The evaluation team then suggests means of resolving the problems. In the external evaluation, personnel assess job-task performance on the job in order to determine the actual performance of trainees and other job incumbents. All data collected, internal and external, can be used as a means of quality control of the training and as input to any phase of the system requiring revision. The three specific outcomes of this phase are instructional effectiveness data, job performance data, and instructional revisions.

Instructional Effectiveness Data

Internal evaluation is planned and conducted primarily to determine whether the ISD instructional development effort has been accomplished. Data are collected not only to assess student progress but to assist in improving the quality of the instruction. The principal question to be answered in the internal evaluation is, Is the instruction providing the students with the necessary information and skills to meet the objectives in a satisfac-

tory manner? In addition, time data and other information from students are collected to provide the basis for making decisions about the revision. Although evaluation is not unique to the ISD process, no set of instructional design and development procedures can be called ISD unless it includes an adequate internal evaluation. Ideally, the internal evaluator would be assigned to a department not directly responsible to the instructional design, development, or delivery system manager. An impartial evaluator will be in the best position to verify that correct procedures have been followed in obtaining the results of the instruction. It is the evaluator's purpose to remove as much of the guesswork as possible from the operation. By careful analysis of the evaluation data, a determination can be made about the problems that surface with the instruction so that appropriate revisions can be made.

Job Performance Data

External evaluation is conducted in order to determine whether the trainees who have completed the training program and are in the field are able to perform on the job. The external evaluator provides the fundamental data for quality control. Those students who have met all of the instructional requirements are followed into the field either physically or by questionnaire. Their performance on the job is then determined by job-performance measures; supervisors' evaluations are also taken into account. Ideally, the external evaluator would base his conclusions principally on actual job performance as measured by the JPM's produced. Often, because of scheduling problems, testing, and other difficulties, some data will have to be collected in other ways. Finally, an external evaluation report is prepared; it contains the conclusions and the data upon which the conclusions were based. Recommendations for any necessary revision are included in this evaluation.

Either by interview or by questionnaire, trainees who have completed the program will be asked about (1) how well they believe they are able to perform the job; (2) the kind and amount of training received since arriving on the job; (3) how well the instruction they received prepared them for the job; (4) the portions of the instruction that were relevant to the job; and (5) which job tasks seem to cause the most difficulty.

From the supervisors of the graduates, information will be collected about how well the graduates are performing on the job, how the graduates compared with those who received another form of training, and in which areas the graduates were inadequately prepared for the job.

From other sources, including an evaluation team, information will be collected about how well graduates scored on the job-performance measures, which JPMs gave them the most trouble, how well the JPMs were administered, and how well the supervisor knows his job.

Instructional Revisions

After the internal and external evaluation reports have been prepared, the data they contain must be used as the basis for deciding which elements of the system require revision. The internal and external evaluation reports will document course performance on an internal basis, and the external evaluation report will have documented the performance of graduates on the job. A careful analysis must be made of the data contained in these reports in order to determine the need for revisions. The need for revisions results from changes in procedures, system characteristics, or other major external changes, as well as from the results of the performance of the instructional program. Revisions can be required in any part of the system, and they can be undertaken to improve performance of the students, to reduce student time required to complete the instruction, or to try to retain an appropriate level of effectiveness at a lower cost. Estimates of the potential benefits of revision are made on the basis of the evaluation data. The specialists within each of the departments concerned with making revisions then decide which trade-offs must be made to make the revision worthwhile.

Data-based system revisions undertaken as a result of careful consideration of the alternatives are the heart of the ISD process. The ability to make good data-based decisions is dependent on the quality of the data collected and on the care with which appropriate conclusions are drawn from those data. It is ordinarily through the revision process, particularly during the early revision cycles, that some of the great payoffs from the ISD process can be realized. An extremely careful effort must be undertaken to establish the basis for comparing training after revisions have been made with prior training effectiveness measures.

This is one of the most significant areas in the IPISD model for making management decisions. All or part of the instruction may have to be revised. Job data, task-selection procedures, JPMS, and settings may all require serious review. The manager must decide what to revise in the context of total resource allocation and scheduling problems. Within any pool of resources, allocating a portion of those resources to the revision of an existing program means that those resources are unavailable for new training course development. Often, the data are very clear and the decisions to revise or not can be made with confidence. Equally often there will be inconsistencies in the data, and the inferences will not elicit the same level of precision; in those instances, the manager must continue the analysis until conclusions can be reached with confidence and a course of action agreed upon.

MANAGEMENT INFORMATION SYSTEM

One of the major functions needing direct management attention in the Interservice Procedures for Instructional System Development approach is the development and organi-

zation of the management information system. Because management information for IPISD training differs significantly from the management information needed for more traditional training, it must be developed and presented in a usable way. Further, inducement must be provided to others to respect and use the data gathered. One planned expectation of the IPISD effort is a reduction in the number of decisions that have to be made on the basis of best guesses and an increase in the number of decisions made on the basis of reasonable conclusions drawn from carefully collected data. The kinds of information that can be most valuable to management include the information gathered about the job, the task list, the criteria used to select tasks for training, the data used to select the setting of the training, and the performance of the trainees. If these data are collected and properly interpreted, the precision with which one can manage training programs can be greatly increased.

It is obvious that these procedures in the IPISD model are different from some current practices. As a result, some resistance to change is to be expected. Although training can convert some opponents to supporters, ISD still requires a large commitment of staff, resources, and time, and that commitment should be planned and provided for from the beginning.

LEARNING THEORY AND ITS APPLICATION TO FLIGHT TRAINING

This section provides the additional information that is necessary for developing aircrew instruction. Its purpose is to apply what is known about how people learn to the development of effective aircrew training. Two theories of learning, behavioral and cognitive, provide principles that have been used to improve the design of aircrew training instructional materials. Behavioral theory is restricted to external, observable behaviors, and attempts to explain why certain behaviors occur. In contrast, cognitive theory attempts to determine how learning takes place, based on processes believed to occur within the learner. Merrill (ref. 8) states:

The most widely applied instructional design theory is based largely on the work of Robert M. Gagné and his associates at Florida State University. This work is often equated with the term Instructional Systems Development (ISD). It assumes a cumulative organization of learning events based on prerequisite relationships among learned behaviors. Gagné's principal assumption is that there are different kinds of learned outcomes, and that different internal and external conditions are necessary to promote each type. Gagné's original work . . . [ref. 9] was based on the experimental learning psychology of the time, including paired associate learning, serial learning, operant conditioning, concept learning, and gestalt problem solving. Recent versions . . .

[ref. 10] have incorporated ideas from cognitive psychology, but the essential characteristics of the original work remain.

Gagné emphasizes the internal and external conditions of human learning (refs. 9, 10). These conditions are derived from research on learning and learning efficiency. The conditions of learning are explained by an information-processing model of learning and memory. This model implies (1) a sequence of internal processes involved in each act of learning; and (2) five different kinds of memory organization which are internally stored as a result of learning, and which exhibit themselves as types of human capabilities (or "learning outcomes"). Both of these conceptions of internal conditions carry implications for the external conditions of learning, implications that can be incorporated into instruction.

Major constructs are the five kinds of memory organization, conceived as the outcomes of learning, and inferred from the learner's performance as learned abilities (categories of things he is able to do). These are:

1. *Intellectual skills*: Symbol manipulation procedures or routines, particularly those seen as using concepts and rules to solve problems
2. *Verbal information*: Stored propositions that relate concepts and that are exhibited by stating information either in oral or written form
3. *Cognitive strategies*: Internally organized processes by means of which the learner modifies (controls) his own processes of attending, learning, remembering, and thinking
4. *Attitudes*: Acquired states that influence the learner's choices to behave in a particular way toward particular objects, persons, or events
5. *Motor skills*: Learned abilities that enable the learner to execute bodily movements having certain properties of timing and smoothness.

As a guide to planning instruction, nine instructional events have been identified that support the learner's cognitive processes. These external instructional events are designed to ensure that the corresponding internal learning process occurs. If these nine external events of instruction are included in each lesson, a greater degree of confidence in the learner's performance of the lesson may be attained.

1. Gain the learner's attention: Alertness
2. Inform the learner of the lesson's objectives: Expectancy
3. Stimulate recall of prior learning: Retrieval to working memory
4. Present stimuli with distinctive features: Selective perception
5. Guide the learning: Semantic encoding
6. Elicit the desired performance: Retrieval and responding
7. Provide informative feedback: Reinforcement

8. Assess performance: Cueing retrieval
9. Enhance retention and learning transfer: Generalizing

The IPISD model has been praised for its emphasis on job skills and on good instructional design. However, it has been criticized for not organizing complex subject matter well and it tends to be topic-oriented and not performance-oriented. To address some of the criticisms, Merrill (ref. 8) extended the ideas of Gagné, based on research by cognitive scientists. He retained Gagné's fundamental assumption that there are different learning outcomes and that different conditions are required to promote each of these different outcomes. Merrill proposed an extension of these fundamental ideas as follows:

A given learned performance results from a given organized and elaborated cognitive structure, which we will call a mental model. Different learning outcomes require different types of mental models; the construction of a mental model by a learner is facilitated by instruction that explicitly organizes and elaborates the knowledge being taught, during the instruction; and there are different organizations and elaborations of knowledge required to promote different learning outcomes. [ref. 11]

Merrill's concept of a mental model is a useful heuristic in designing training programs for such complex skills as flying an aircraft. The basic idea is that a person develops an internal model of the world to reason and explain things about the world. Montague states that:

Mental models are composed of autonomous objects associated topologically with others, rules for their interaction that allow them to be run in one's imagination or mind's eye and the outcomes assessed. They assist human reasoning by producing explanations or justifications of complex system behavior. They are mnemonic devices or learning devices Thus, they aid in the apprehension of how systems work and provide a strong means for generating expectancies about how things are done, should be done, or the consequences of certain actions. [ref. 12]

It is important to provide a learning environment that promotes the development of mental models. The use of simulators and simulation in aircrew training is one way to provide this performance-related context and to aid in the development of appropriate and accurate mental models. Montague states:

In training with simulation, we are attempting to help people build up their representation of the physical world to be able to operate equip-

ment effectively, and we must be able to design training and training devices to allow the most effective buildup of appropriate mental models What is required for training simulators/devices is that they must provide the cues, the opportunities for trainees to respond, make and correct errors, and observe the consequences of their actions. [ref. 12]

Cognitive scientists have proposed what they call the "situated learning model." Brown et al. argue that "knowledge is situated, being in part a product of activity, context, and culture in which it is developed and used" (ref. 13). They propose "cognitive apprenticeship," which honors the situated nature of knowledge. They identified six useful strategies: (1) apprenticeship, (2) collaboration, (3) reflection, (4), coaching, (5) multiple practice, and (6) articulation. In referring to situation learning McLellan states that this knowledge must be learned in context — in the actual work setting or in a highly realistic or "virtual" surrogate of the actual work environment (ref. 14). Virtual realities are defined by Henderson as a multimedia environment that provides users a sense of participating in realities different from their own (ref. 15). He feels that the main purpose of virtual realities is to provide experiences that are transferable to reality. He states that they are equivalent to high-fidelity simulations produced by using interactive media or with specialized systems such as aircraft simulators.

McLellan cites an example of how the situated learning model can be implemented using virtual reality by referring to a scene in the movie *Firebirds* showing simulator training of an Apache helicopter crew. McLellan states:

Two trainees, a pilot and a gunner, enter a sophisticated simulator, a virtual environment that is controlled by their commanding officer, the instructor, and an assistant who are in a nearby room equipped with a set of computer controls and video monitors that show the trainees and what they see and do and say in the simulator. Within the simulated helicopter flight, the environmental conditions are controlled, and modified, by the commanding officer to simulate increasing difficult conditions of terrain and enemy attack. Apprenticeship is present since the commanding officer decides what level of difficulty the trainees are ready for in each successive simulated flight. The instructor provides coaching in the form of feedback on the trainees' performance during each simulated flight. Collaboration is present in terms of teamwork between two members of the helicopter flight team, and also in the verbal interplay between trainees and instructor

Teamwork and coordination are necessary not only between crew members on a single helicopter, but also between helicopter crews working

in tandem to carry out a mission. The simulation provides the opportunity for multiple practice where different factors are articulated This helicopter simulator is a form of virtual reality: it is a highly sophisticated surrogate of an Apache helicopter that is supplemented with powerful feedback mechanisms This virtual environment is used in accordance with the Situated Learning Model of training Another example of how virtual reality can be paired with situated learning is a training program for airline pilots, line-oriented flight training, known as LOFT The LOFT program was devised to provide practice in team building and crisis management. [ref. 14]

It is important to distinguish between simulation and simulators. Hays and Singer define simulation as "the ongoing representation of certain features of a real situation to achieve some specific training objective" (ref. 16). Simulators are "the media through which a trainee may experience the simulation." A simulator is usually considered a single piece of equipment that represents the aircraft. Hayes and Singer go on to say:

No matter how a training device is designed, no matter what its level of fidelity, it will not be an effective trainer if it is not used properly. Likewise, it is not possible to design an effective device if the task to be trained is not understood and if the context of instruction is not compatible with the training device. A total training system perspective must guide training development to insure that the most effective training strategies are followed. [ref. 16]

Gagné lists three main characteristics of simulators: (1) they represent a real situation, (2) they provide controls over the situation, and (3) not every aspect of the situation is simulated.

Gagné's third characteristic is important in distinguishing between training simulators and engineering simulators. Jack Thorpe, Defense Advanced Research Projects Agency (DARPA), distinguished between engineering simulation and training simulation. He emphasizes that data generated in the context of engineering simulation may not be applicable in the context of training simulation and vice versa (ref. 17). The purpose of engineering simulation is "to provide a test-bed for studying the effects of engineering parameters on performance," whereas the purpose of training simulation is "to develop aircrew skills" (ref. 17). *The approach used in engineering simulation is to try to duplicate all the important flight conditions; the approach used in training simulation is to identify the skills to be trained and the types of training media that should be used (what, where, how often).*

Hays and Singer note that in a training simulator it may be necessary to depart from realism in order to provide the most effective training (ref. 16). As an example, they

mention the addition of instructional features, such as stop-action, lesson restart, and enhanced feedback, all of which reduce the realism of the training situation, but enhance learning. Also, Thorpe remarks that training simulators exist within a total context, a total training system, and that if taken out of context they are no longer training devices (ref. 17). Any change in one component of the training system will likely affect the training effectiveness of the entire system. Because a mix of training devices can sometimes provide the most effective training, it is important that managers not look at a simulator by itself but rather focus on the entire training system.

When simulators are mentioned, the first thoughts of many people turn to high-cost, full-mission (high-fidelity) simulators. There is a common sense conception among many people that if skills learned in a simulator are going to be transferred to the aircraft, then the stimuli and associated responses in the simulator must be similar to or identical to those experienced in the aircraft. This misconception has produced some very high-cost simulators of questionable training value. Thorpe makes the point that there is the tendency to equate "fidelity" with "high fidelity," which is counterproductive because it locks us into one training strategy (ref. 17). He feels that the goal of training equipment design should not be geared to some hypothetical level of fidelity, but to the production of a whole training *system* that will make use of the most creative instructional strategies available (including low-fidelity devices). In fact, a 1978 Air Force Human Resources Laboratory study showed that flight simulators with very high fidelity provided too much information for novice trainees and actually distracted from training (ref. 18).

Hays and Singer list three hardware reasons and three instructional reasons for using training simulators (ref. 16). The hardware reasons are (1) safety, (2) cost, and (3) device availability. The instructional reasons are (1) performance measurement, (2) instructional flexibility, and (3) the capability of "intelligent" training simulators. The hardware reasons are self-explanatory; however, the instructional reasons need some amplification. Measurement is important to knowing how the trainee is performing; it provides feedback to the student, and forms the basis of individualized instruction. Instructional flexibility is a strength in training simulators. "The instructor can freeze an instant, compress time, or make it run backwards, even alter the sequence of tasks to enhance all instruction" (ref. 16). Also, training simulators "can be simplified, in order to give an overview or to provide initial instruction at a reduced difficulty level." Finally, training simulators can be made more "intelligent" and be able to perform many of the current simulator instructor functions.

The ultimate value of simulator training depends on the extent to which skills learned during that training can be utilized later in an aircraft. The process of subsequently using simulator skills in an aircraft is usually called *transfer of training*, or simply transfer. That is, skills learned during simulator training are said to transfer to the

aircraft. The transfer of training is a complex process. It depends not only on *what* is learned, but on *how* and under what *conditions* the learning occurs. Transfer of training and cost effectiveness are covered in detail in Chapter 4; however, it is necessary to introduce the concept of transfer of training at this time because of the pervasive effect it has on the design and development of aircrew training systems.

LEARNING PROCESSES IN AIRCREW SKILLS DEVELOPMENT

To understand the learning processes involved in aircrew skills development it is necessary to understand the kinds of tasks that are involved in piloting an aircraft. Hays and Singer define a task as a series of goal-directed transactions controlled by one or more "programs" that guide the operations by a human operator of a prescribed set of tools through a set of completely or partially predicted environmental states (ref. 16). There are five man-machine interaction tasks in piloting an aircraft:

1. An indicator on which the activity-relevant indication appears (stimulus) (e.g., instruments, warning lights, and horns)
2. A cue, or sign that calls for a response (decision to make corrective action) (e.g., checklist, instrument reading different from expected, flashing light, a special sound)
3. A control object to be activated (e.g., aircraft yoke, throttles, rudder pedals)
4. The activation or manipulation to be made (actual behavior sequence in executing the selected motor action) (e.g., push forward, pull back, turn clockwise)
5. The indication of response adequacy (e.g., instrument reading normal, glide-slope indicator showing on glide slope, flashing light goes off)

Generally, the feedback from one task cues the next task to be done. These are known as continuous tracking tasks and are the most difficult type of tasks performed in any job. Man's perception receptors are involved in sensing the incoming stimuli. His cognitive processes are involved in cue development by interpreting the stimuli and giving them meaning, and deciding on what corrective action to take. His muscle effectors are involved in producing the motor responses that implement the corrective action by manipulating the controls. Then the cycle is repeated. Flying an aircraft requires continuous corrective action involving perceptual senses, cognitive activity, and motor responses.

The previous paragraph sets out the tasks that are involved in flying an aircraft. Now, let's look at the learning processes involved in complex skills development: cue development, discrimination, generalization, and mediation. A more detailed discussion

of learning processes in aircrew skill development is provided in chapter 3 of reference 19, from which the following information has been excerpted.

Cue Development

The development of cues and the selection of correct responses to those cues are important aspects of flight training. A cue is a stimulus that has acquired meaning, that is, it conveys information that is understood by the airman. The bases for cues are stimuli, although a stimulus is not a cue by itself. A stimulus refers to a physical object or to an event that can activate a sense receptor.

Discrimination

Discrimination is a process of interpreting stimuli (i.e., cue development) and selecting appropriate responses. It is simply the recognition that a given stimulus or response is different from another stimulus or response. Discriminations are complex processes, and they can be difficult to learn. The more complex the skill involved in aircrew performance, the larger the number of moment-to-moment, even instant-to-instant discriminations that must be made. Also, as task complexity increases, discriminations depend on very subtle differences in patterns of numerous stimuli. The difference between a novice and an expert when performing complex tasks is that the expert has learned to derive more detailed information from the cues. He can discriminate subtle differences that a novice cannot. The expert can also translate the subtle meanings into equally subtle control inputs.

A training program that makes use of an "aircrew skills hierarchy" can aid the trainee in learning to make discriminations. The purpose of developing skill hierarchies is to determine which skills underlie, or are components of, skills higher in the hierarchy so that learning the higher ones can be made easier by building upon previously mastered skills that are lower in the hierarchy. The same strategy can apply to learning discriminations. Complex discriminations can be built on separately learned basic discriminations. For instance, if a student has previously mastered distance-estimation tasks and the coordination of control inputs in response to visual cues, these discriminations can be used to guide his inputs to flight controls when he is later approaching a tanker for in-flight refueling.

Generalization

Generalization refers to the use of previously learned skills in situations that are different from the situations in which they were learned. Generalization occurs to the extent that a

given situation is interpreted as being similar (based on cue information) to a previously experienced situation. The cue information is the meaning conveyed by the stimuli present in the two situations. Therefore, cues learned in a simulator can be generalized to (used in) an aircraft if the cues have the same meanings in both vehicles. The physical stimuli can vary but the cues mean the same thing. Consequently, the simulator student should learn to use cues that he will need in order to perform in the aircraft by concentrating on the "meanings of stimuli" available in the simulator rather than on the physical characteristics of those stimuli.

The learning discussed in the preceding paragraph might be described as generalizing cue discriminations, a process that underlies the learning of all skills. This process was implied in the earlier discussion of hierarchies, that is, building new discriminations on those already learned. Cues and responses associated with previously learned skills become incorporated into new skills through this process. Generalization of the discrimination among cues is the basis for the generalization of responses appropriate to those cues. If a response has become associated with a cue, and refined and honed according to the requirements dictated by the cue in all its subtle aspects, then it will be available to the extent that the cue itself is recognized in a subsequent situation. The challenge in simulator training is to teach cue discriminations in such a way that cue subtleties remain clearly recognizable in the new, different stimulus complex presented in an aircraft. When simulator training accomplishes this, aircrews will transfer associated simulator-learned responses to the aircraft as well.

Mediation

The psychological process involved in seeking and recognizing familiar cues in changing situations is called mediation. That is, the generalization of previously learned discriminations to a situation at hand is an intermediary process that provides meaning for the situation. It comes between, or mediates, the acts of sensing a stimulus and responding to it. Mediation occurs any time a person interprets a stimulus and acts according to that interpretation. Mediations underlie all skills, and mediational explanations of transfer of training are important in simulator training because they focus attention on related learning processes rather than on the physical features of the device and the responses that can be performed in it. Simulator training should emphasize the mediating processes that enable students to establish cue meanings and cue and response discriminations, and to generalize skills being learned in the device to the stimulus situation to be encountered in the airplane.

It has been demonstrated that training devices that are low in physical fidelity can nonetheless be effective for teaching procedures. Prophet and Boyd found that aircraft-procedures training in a cockpit mock-up made of plywood, photographs, and dowel

rods transferred to an aircraft as well as did corresponding training in a high physical-fidelity device (ref. 20). Photographs of cockpit switches in the mock-up symbolized the real switches in the aircraft, and the symbolic process of pretending to reposition those switches was just as useful when learning to perform cockpit procedural tasks and their sequences as when the tasks were trained in the aircraft. Furthermore, the necessity for written materials and oral instruction in aircrew training illustrates the extensive dependence on symbolic meanings. With appropriate experience, mental or imaginative rehearsal can be effective for learning many tasks or for improving performance in them. Johnson found that low-fidelity training devices could be used to teach procedural skills when an imagery strategy was used in the training (ref. 21).

The importance of mediation in simulator learning becomes even more obvious when one considers the pervasive role of verbal mediation — a process with no objective fidelity whatsoever — both in training and in operational performance. The profound role of language in learning to discriminate among cues and to generalize those discriminations is easily established. Without language, aircrew training would be a chaotic enterprise. Consider training a student without any words, oral or written, to explain things to him or to tell him what to do or how to practice. Not only does the instructional process itself depend on previous mastery of this mediational system, but the student must learn new uses of it. He must use language overtly for communication during task performance; but probably more important, he must employ language covertly to clarify most of the cues he will use, and to guide his discrimination of cues and the responses associated with them. Furthermore, this last use of language often increases as an airman matures.

Because of the role verbal processes can play in complex performance, such as air combat maneuvering, and because verbalizations can be brought under conscious control, language is a prime mediational vehicle for teaching even nonverbal, perceptual motor skills. Eventually, a pilot may learn to use, say, only visual perceptions of the rate of change of a compass heading to guide some particular control input. But rate of change is vague at best to a novice. He must first read the compass as headings or degrees — words — while probably saying to himself, "That's too much; that's about right." If one teaches the novice how to use language as a mediational vehicle while in training, that is, to talk to himself about what to notice and what to do, he will be able to learn more rapidly to discriminate perceptual and kinesthetic cues and associated motor responses. The end result will be a well-established, coordinated, complex habit that eventually may require little or no verbal guidance.

Aircrew trainees should be taught to verbalize the discriminations they are learning, and the verbalizations should concentrate on the selection (discrimination) of appropriate cues, including ongoing kinesthetic feedback from control movements. To enhance the effectiveness and efficiency of simulator training, equal emphasis should be

given to how the student is processing information, how and why he selected or failed to select particular cues, and what he should do to improve the processing of the information he obtained from those cues. Mediation of all types permeates every aspect of aircrew training and performance. Therefore, these procedures should be specifically targeted in training objectives.

Caro points to the central role mediation plays in computer-based training:

Through mediation the trainee can substitute touching a computer-based representation of, for example, a toggle switch for the actual act of moving the switch in the aircraft. In this way, the trainee can learn quite readily to operate rather complex systems by having them simulated on the computer display screen [The] computer terminal is used as a low-cost simulator of aircraft systems and through mediation, provide[s] training in the operation of those systems. [ref. 4, p. 246]

However, Caro points out that there is a practical limit to the use of mediation and low-cost simulators in training.

Although low-cost simulators can be effective in training, higher cost devices also are needed in a total training program. Low-cost devices can be used to train selected tasks that can be represented realistically at low cost, but many tasks involved in flight training cannot be trained in simulators that represent so few cues and responses. Complex tasks that are more dependent on variable rather than fixed procedures and on crew coordination, timing, and situational considerations cannot be practiced efficiently in such simple devices. Most aircrew training programs recognize this fact and incorporate mission simulators that simulate all — or nearly all — of the features of an aircraft and its environment, as well as devices such as cockpit procedures trainers that simulate only a subset of those features. Regardless of the complexity of the tasks to be trained or the realism and completeness of the simulation of those tasks, the learning processes involved in efficient simulator training are the same. The manner in which the simulator is used in training must attend explicitly to cues, discriminations, generalizations, and mediators if the intended aircrew skills are to be developed (ref. 4, p. 247).

CONDUCTING AIRCREW TRAINING

Since flying an aircraft requires continuous corrective action involving perceptual senses, cognitive activity, and motor responses, these skills will have to be acquired through the learning processes described above and through instruction and practice in simulators and aircraft. *The importance of cognitive training, situational awareness, and cockpit*

resource management in flying airplanes has not been emphasized enough in the past. Singer points out that in the psychomotor domain it is becoming more apparent that cognitive processes and strategies are much more involved in skill acquisition than heretofore realized (ref. 22).

Cognitive training should be employed systematically during aircrew training to provide a context for skill performance and to aid in learning particular cue and response discriminations. In academic training, students should acquire knowledge of the tasks they are to perform through briefings and homework. Students should be encouraged to rehearse tasks mentally and to think them through before attempting them in simulators, and again after they have been practiced. The debriefing of students should highlight the adequate aspects of performance, as well as problems to be resolved during subsequent training. Successful uses of cognitive training include the work of Prather with T-37 student pilots. By having student pilots listen to audio recordings that prompted mental practice of what to do, when to do it, and why to do it in landing the T-37 aircraft, Prather found that the students were able to perform significantly better on both procedures and on landing (ref. 23).

Cognitive training is not restricted to verbal information. For example, Waters et al. report that flying skills, such as scanning the horizon, interpreting instruments, and learning procedural sequences, can be learned from photographs, workbooks, and audio-visual devices (ref. 24). They also reported on the results of a study using multimedia materials to teach the overhead landing pattern. The program produced student pilot performance that was consistently superior in both cognitive component test scores and in the transfer of training to the acquisition of complex perceptual motor flying skills. Crawford and Hurlock used a PLATO IV touch-screen to present graphic simulations of the front panel of the S-3A Copilot Integrated Control System Panel Multipurpose Display (ref. 25). The results indicated that computer-trained students outperformed students trained by using the classroom and a high-fidelity simulated-position trainer, and that there was a cost savings as well.

Cognitive training is important, but there are other aspects such as guidance and feedback that are essential in learning aircrew skills. In order for the training to be efficient and effective, the learner must do or have available to him the following:

1. Attend to the instruction
2. Know what is expected (performance objective)
3. Recall prior knowledge
4. Perceive the distinctive features of incoming stimuli
5. Receive guidance in the learning
6. Perform the desired actions

7. Receive feedback on correctness of actions
8. Have performance assessed
9. Retain the learning and transfer it to other situations

These are the nine events of instruction that Gagné proposed to help ensure effective training in simulators, aircraft, and all other media.

CONCLUSION

This chapter has provided an overview of training system design and development that it is hoped will be useful to technical managers in planning and regulating civil training delivery systems. It addressed training as a major concern of managers, because training is essential to the safe and effective operation of all helicopters, as well as tilt-rotor and tilt-wing aircraft, in the current and future national airspace. The problem of how to ensure adequate training without overtraining or undertraining was addressed. A systems approach to the processes and procedures of instruction that are thought to be the most effective current means of evaluating, developing, and implementing alternative solutions to instructional problems was presented. This can be done by determining instructional needs and priorities, by developing effective and efficient means of fulfilling needs, by implementing solutions in a competent manner, and by assessing the degree to which the output of the system meets the specified needs.

The Interservice Procedures for Instructional Systems Development (IPISD) model, which was prepared for the U.S. Armed Forces by Branson and his colleagues at Florida State University, was explained in some detail. IPISD is a five-phase model that describes the functions necessary to analyze instructional needs; to design, develop, and implement instruction; and to maintain quality control of instruction. Learning theory and its application to flight training stressed the conditions of learning as specified by Gagné. Gagné's work was modified by Merrill to include the concept of mental models, a useful heuristic in designing complex skill-learning programs.

Simulators were discussed in the context of virtual reality and situated learning as a way of providing a performance-related context for training. Simulators were viewed as an important component of any aircrew training program; however, the importance of maintaining a systems view in dealing with training programs was noted. With the simulator in its proper context, that is, properly used, learning processes — cue development, cue and response discriminations, generalization, and mediation — were discussed. The chapter was concluded with a brief discussion of how the information presented can be used to conduct aircrew training.

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4 TRANSFER OF TRAINING AND COST-EFFECTIVENESS

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SUMMARY

A theory for evaluating simulator cost and training effectiveness is developed. Models for expressing the relationship between training factors and the time required in the aircraft, and for determining optimal cost-effectiveness are presented and illustrated. The use of an exponential decay function, which directly expresses the assumption of diminishing returns to solve for the point of optimal cost-effectiveness, is defined and illustrated. A distinction is made between cost-effective simulator use and cost-effective simulation, and a three-phase experimental process for investigating the many factors that affect training and transfer of training is described. It includes simulator design factors, simulator factor enhancement or augmentation, instruction factors, and optimal simulator use. This three-phase process includes the use of performance experiments, in-simulator transfer-of-training experiments, and field transfer-of-training experiments.

INTRODUCTION

Cost-effectiveness analysis (CEA) refers to methods whereby alternative means of achieving an end result, or a product, can be compared in terms of cost and effectiveness. For our purposes, effectiveness means *training effectiveness*, which is measured by means of appropriate performance criteria. More specifically, training effectiveness refers to the proficiency level achieved by individuals as a result of their completion of a training process. When applied to training effectiveness problems, CEA is sometimes referred to as cost and training effectiveness analysis (CTEA), but we retain the term CEA for generality. The term *proficiency* is defined here to mean the ability, acquired through training and practice and as a result of certain inherent characteristics, to perform at some certain level on specified tasks. Proficiency level is determined by appropriate measures of performance, which may range from paper and pencil tests to precise measures of control, (e.g., hover) to instructor ratings of overall ability. Cost refers to the measurement in dollars of the resources consumed during a training process.

CEA is a special case of systems analysis and cost-benefit analysis. It differs from the more general cost-benefit analysis in that performance does not need to be val-

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ued in dollars. In cost-benefit analysis the alternative products are valued in dollars and a cost-benefit ratio is obtained. Alternatives may then be compared in absolute terms (dollars) by comparing the cost-benefit ratios. The general form of CEA involves comparisons of the costs of the alternatives and the training effectiveness of the alternatives. Thus, it actually involves a cost analysis, which compares the alternatives in dollars, and a training effectiveness analysis, which compares the alternatives in terms of performance measurements. CEA does *not* require that performance be valued in dollars, but it does require that either performance or cost be held equal if a nonambiguous answer to the question of which alternative is "best" is required. Holding performance between alternatives equal has been done classically in designed transfer-of-training experiments by constraining performance such that proficiency is held equal; specifically, training to a fixed criterion level on a transfer task.

It is assumed, in this regard, that the user of CEA desires to know which alternative is "best" from either a cost or training-effectiveness perspective. If neither cost nor performance is held equal, an ambiguous result may be obtained. This is not necessarily a problem, however, and may even be desirable in some circumstances. In this case a figure of merit is provided, and the user then has a choice of more than one combination. To illustrate an ambiguous result, consider that one outcome in a two-alternative comparison may be that alternative B costs more than alternative A, but that B produces students with a higher proficiency level. That is, alternative B is "best" in terms of training effectiveness, but alternative A is "best" in terms of cost. To solve the difficulty, one needs to place a value on the performance *difference* between A and B.

To illustrate this, assume a two-alternative comparison with the following results:

Alternative	Cost	Proficiency level
A	10	7
B	13	9

The costs are in dollars and the proficiency levels are (arbitrary) averages for a group of students. Assume that proficiency has been measured by a suitable metric which could be, for example, a proficiency rating or the number of acceptable or better landings in 10 attempts. Alternatives A and B are two different methods of training, that is, B is not simply more A. Further, assume that the results shown are the only information available. (Note that this would often be the state of affairs for a practical situation in which data were gathered to compare two alternatives.) Thus, we do not know the relationship between costs and proficiency level for either alternative or for any other proficiency levels.

In the above example, the results obviously do not provide a clear answer to the question of which alternative is best. Alternative B costs more, but it produces a higher level of proficiency. Given information about the nature of the performance measurement, one could make an *informed guess* about which alternative would be the most cost-

effective while meeting specified training requirements, but more information is required to reach a *mathematical solution*. This necessary additional information would provide a comparison of results for equal performance or equal cost.

There are four choices of where the comparison in terms of constants (values held equal) could be made. We could compare costs at a proficiency level of 7 or 9 or we could compare proficiency levels at a cost of 10 or 13. Suppose we wanted to make the comparison at a proficiency level of 9. Then the additional piece of information we need is the cost of the *additional* A-alternative training needed to produce a proficiency level of 9. If we knew the relationship between the levels of A-training and performance we could estimate this value. Suppose we have this information and obtained the following where A_1 is the original alternative, and A_2 is an increased amount of A_1 :

Alternative	Cost	Proficiency level
A_1	10	7
A_2	12	9
B	13	9

It is now clear that at a proficiency level of 9, A_2 is the most cost-effective alternative relative to alternative B. Now, suppose that a proficiency level of 7 is acceptable and, given the requirements of the training system, that it is only necessary to train to this level. Then the "equal performance" comparison that is desired is at proficiency 7. Again, suppose we know the relationship between the levels of alternative-B training and performance, or that we have obtained empirical data on specific levels of B and obtained the following result where B_1 is the original alternative, and B_2 represents decreased training using the alternative-B.

Alternative	Cost	Proficiency level
A_1	10	7
A_2	12	9
B_1	13	9
B_2	9	7

It is clear from the above that at proficiency level 7, B_2 is the best alternative. Thus the answer to the question of which alternative is best depends on the level at which proficiency is held equal.

It should be noted here that the preceding discussion deals only with the case in which distinct alternatives are considered, that is, the comparison of one method of training versus another. In a complex real-world environment, interest is more likely to center on the optimal *combination* of training factors. In the above example, interest would likely center on the combination of training alternatives A and B that would produce the

most cost-effective performance. This is very much the case when training devices with different levels of complexity, realism, and cost are the training factors under consideration.

In practice, it is desirable to collect performance and cost data at various selected levels of the training factors X_1, X_2, \dots, X_n that are of interest. The levels of these factors are specifically chosen to maximize the information in a *designed* experiment. In an *undesigned* experiment, data are collected at the levels of the factors that exist naturally or that have occurred as a result of changes to an existing system. In the latter case, sources of confounding, which may exist if more than one factor has been changed, generally cannot be resolved statistically.

COST-EFFECTIVE ALLOCATION OF RESOURCES

Ideally, we would like to allocate all necessary resources to a training process in the most cost-effective manner. In theory, we could do so if we knew the various relationships between performance and the costs of training factors at different levels. It is worthwhile to understand this theory, for it lends insight into the objectives and problems of cost-effectiveness analysis. The theory assumes that we know (or can reliably estimate) the training effectiveness of all combinations of training (input) factors. Further, it is assumed that the ratio of costs for input factors is constant. For the sake of illustration, much of what follows will assume only two training factors. For our purposes, one of these can be considered training in the real task or aircraft, and the other can be considered simulator training. Much of what follows draws heavily from String and Orlansky (ref. 1).

BUDGET-CONSTRAINT LINE

A budget-constraint line represents the combination of inputs that results in a constant cost. There are of course an infinite number of possible budget-constraint lines, one for each possible budget. In practice, however, one would be interested in only a limited range of these. In the case of simulator training and aircraft training, there is essentially only one budget-constraint line, although there will be different budget-constraint lines for different simulator configurations.

Figure 1 illustrates three budget-constraint lines representing three budgets, C_1 , C_2 , and C_3 . Note that under the assumption of constant cost ratios, these lines will necessarily be parallel. In the example shown, training factor 2 costs 1.5 times as much as training factor 1, per unit of time. The training input factors have been labeled X_1 and X_2 in accordance with the convention of the general linear model. Thus, they are appropriately viewed as factors within a model that relates their effects to performance. The levels of the factors are in turn directly related to costs. For our purposes, assume that training factor 1 is simulator training and that training factor 2 is aircraft training.

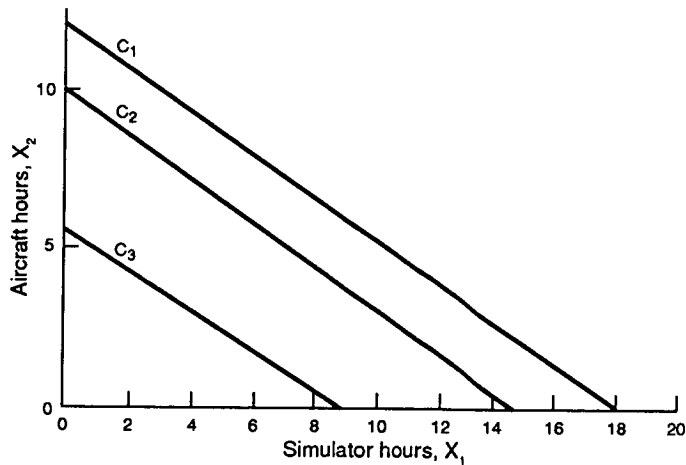


Figure 1. Budget-constraint lines.

PRODUCT ISOQUANTS

Product isoquants are defined here as the contours of equal performance across the range of interest for the training factors. They may be described as the combinations of training factors that result in equal performance. In theory there are an infinite number of these isoquant lines, but in practice we would generally be interested in only a limited number of them within a few categories of performance. In any case, it must be noted that they are theoretical until verified empirically.

Product isoquants are illustrated in figure 2. It should be noted that in theory product isoquants can take a variety of shapes; the lines drawn in figure 2 show a characteristic called *continuous convexity*. This characteristic is consistent with the results published in the literature in many instances and is consistent with the expectation for many training factor environments, that of *diminishing returns*. That is, as we apply more and more of a given factor beyond some nominal amount, we get less and less *additional* training-effectiveness benefit.

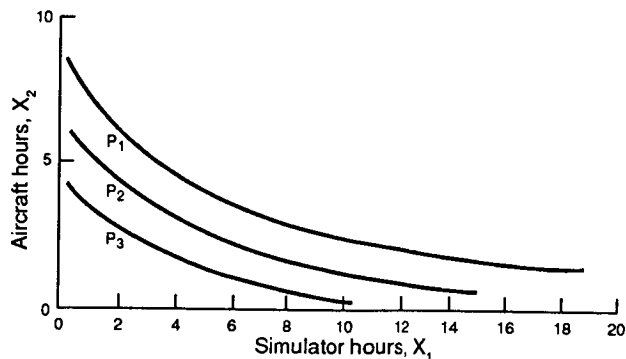


Figure 2. Product isoquants.

When a product isoquant shows continuous convexity, there will be a unique point of tangency between it and a budget-constraint line. That point of tangency gives the combination of training factors that minimizes cost for that specific level of performance defined by the product isoquant. At the point of tangency, there is no other equal-cost mix that will result in a higher level of training effectiveness, and there is no other combination of training factors that will result in the same level of training effectiveness at an equal or lower cost. This can be seen in figure 3 where an example is given for the training factors of simulator and aircraft hours. The data for this hypothetical example are given in table 1.

Table 1. Illustrative Combinations of Simulator and Aircraft Hours

Combination	Simulator hours	Aircraft hours	Cost ^a	Performance ^b
1	0.0	7.3	\$1095	90
2	2.0	4.0	800	90
3	4.3	1.3	625	90
4	7.5	0.5	825	90
5	11.0	0.4	1160	90

^a Simulator cost at \$100/hr; aircraft cost at \$150/hr.

^b Arbitrary equal performance value, which is assumed to be a criterion level.

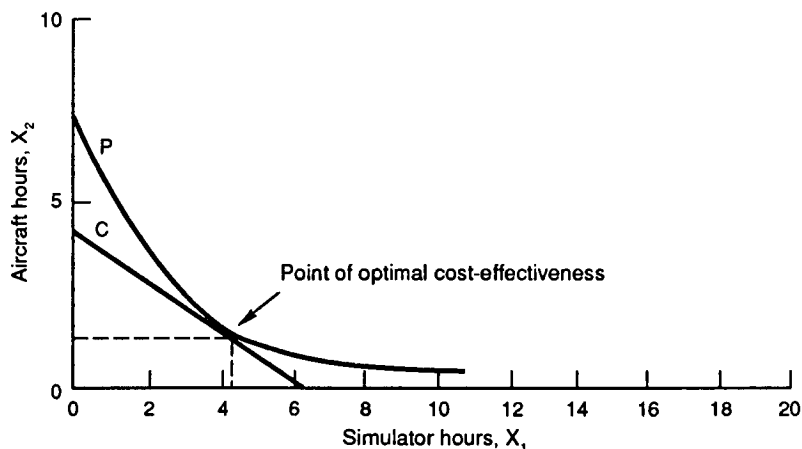


Figure 3. Point of budget-constraint line and product isoquant giving point of optimal cost-effectiveness.

This observation allows us to see that at the point of tangency (fig. 3), the slopes of C and P are equal. *At this point*, the rate of substitution — which is the rate at which training-factor unit times can be substituted for each other without affecting performance — is equal to the ratio of the costs of the training factors. Note that the theory of diminishing returns dictates that this rate change along the range of the factors. (If it did not, product isoquants would be represented by a straight line, and the substitution ratio would be a constant.) The average substitution ratio over a limited range and in discrete terms is what Roscoe calls the incremental transfer effectiveness ratio (ITER) (ref. 2), and the plot of these over the range of interest for the training factors would represent the incremental transfer function (ITF). To keep matters straight, the term substitution ratio (SR) will be reserved to refer to a point value, and the term ITER will refer to the discrete analogue of the substitution ratio.

The fact that the rate of substitution at the most cost-effective point is equal to the ratio of costs can be used to define some relationships mathematically. Specifically, at the optimal cost-effective point,

$$SR = - C_1/C_2 \quad (1)$$

where C_1/C_2 is the ratio of unit costs (e.g., an hour of training time) for training factors X_1 and X_2 . (Note that the negative sign reflects the slope direction.)

The ITER may be referred to as the discrete form of the substitution ratio,

$$ITER = (X_{2,t-1} - X_{2,1}) / (X_{1,t} - X_{1,t-1}) \quad (2)$$

where $X_{2,t}$ is units of factor X_2 at measurement t , and $X_{1,t}$ is units of factor X_1 at measurement t .

The ITF presents a plot of ITERs along a product isoquant for suitably small units of measurement t . (It should be noted that the sign of the actual slope has been reversed in this formulation. This was done to create positive values of the transfer ratio to represent positive transfer; it presents no problem in the analysis.) The significance of this is that if the ratio of costs is known, if the general form of the ITF is known, then the point of optimal cost-effectiveness can be estimated. In practice, this relationship would generally have to be estimated from data. However, unless this relationship is known, or can be reliably estimated, the most cost-effective combination cannot be determined. Further, a single optimal combination cannot be determined unless continuous convexity is present. Continuous convexity will be referred to herein as the *assumption of diminishing returns*. However, it cannot be overemphasized that this assumption is just that, an assumption. Whenever possible, of course, one should draw conclusions from data, rather than make assumptions.

MEASUREMENT OF TRAINING EFFECTIVENESS

In the preceding section, it was suggested that training effectiveness can be measured in a variety of ways, but that to ensure an unambiguous answer to a cost-effectiveness analysis problem, training effectiveness must be held equal. (Costs may also be held equal, but our focus here is on training effectiveness.) What follows are descriptions of historical attempts to measure training effectiveness in meaningful ways that also accommodate cost comparisons. Though it is important to understand that cost-effectiveness cannot be determined if performance is not held equal, it is not strictly necessary to constrain performance in a transfer-of-training experiment by means of trials-to-criterion measurement. In fact, there are advantages to not constraining measurement by transfer testing only to criterion, for more information can be obtained on transfer performance. However, if cost-effectiveness is to be determined, there must be a way to obtain trials-to-criterion equivalency data. This can be done by having experts determine when an acceptable performance level has been obtained, and then using that information to extract trials-to-criterion data.

Percent Transfer

Percent transfer is a measure of the amount of training required to reach criterion performance by an experimental group relative to a control group. The traditional experimental design paradigm for testing training effectiveness is illustrated in table 2.

Table 2. Illustration of Transfer-of-Training Experimental Paradigm

Training factor A	Amount of training	Transfer task
Group 1 (experimental)	E	Y_E
Group 2 (control)	None	Y_C

Notes: E is some value of time or the number of trials chosen by the experimenter; Y_E is performance on the transfer task by the experimental group; Y_C is performance on the transfer task by the control group.

If performance on the transfer task is measured in terms of time to criterion, then the percent transfer of the experimental group relative to the transfer group is given by

$$\text{Percent transfer} = (Y_C - Y_E) (100) / Y_C \quad (3)$$

Thus, for example, if it takes the experimental group half as long to reach the criterion as it takes the control group, then the percent of transfer is 50%. If there are a number of experimental groups, each training in the simulator for a different number of trials, the percent-transfer values would provide a relative comparison of the amount of time saved on the transfer task. This measure does not take into account the amount of

time (or cost) that was required to train the experimental group and thus has little value in CEA.

However, it is instructive to consider performance-measurement issues relative to this measure since the implications carry over to more useful transfer effectiveness metrics. First, note that measurement of performance on the transfer task is described in terms of time or trials to criteria, which conveniently constrains the results to "equal performance." With "equal performance" on the transfer task established, all that remains is to determine the cost of the alternatives to determine the most cost-effective alternative.

If performance on the transfer task is not measured in terms of the amount of resources consumed to criterion, the interpretation of the result is affected. In fact, the usual interpretation of percent-transfer and of transfer-effectiveness ratios is dependent on this level and type of measurement. It is important to note that under the definition of this metric, and under the general idea of trials or time to criterion as a performance measurement, the transfer task is also a training factor in the sense that "training" on the transfer-task device (e.g., the aircraft) takes place as an integral part of the transfer-of-training paradigm. Thus, we properly speak of performance on the transfer task as the dependent variable, and training on the transfer-task device as a training-factor level within a general model of cost-effectiveness. Strictly speaking, these measures, which constrain performance, are not dependent measures in the usual sense, but rather are indications of the level of training on the transfer factor for specific performance conditions. This will be seen more clearly when we look at the relationship between the general linear model and the substitution ratio.

Transfer-Effectiveness Ratio

The transfer-effectiveness ratio (TER) relates the time saved on the transfer task relative to the time spent on the training factor. This is defined by the following relationship:

$$TER = \frac{Y_C - Y_E}{X_E} \quad (4)$$

where

Y_C is the time for a control group to reach the performance criterion on the transfer task

Y_E is the time for the experimental group to reach the performance criterion on the transfer task

X_E is the time on the training factor task for the experimental group

The transfer-effectiveness ratio may be computed over levels of the training factor, in which case it is called the cumulative transfer effectiveness ratio (CTER) by Roscoe (ref. 2). The TER provides a measure of the rate at which the time for a training

factor can be substituted for the time on the transfer task to reach the criterion across levels of the training factor. The TER is a special case of the ITER in which the ratio is computed relative to a control group.

General Form of the ITER

The ITER can be expressed in the more general form

$$\text{ITER} = \frac{X_{2,t-k} - X_{2,t}}{X_{1,t} - X_{1,t-k}} \quad (5)$$

where

- X_1 is time on training factor X_1
- X_2 is training time on transfer factor X_2 to reach criterion
- t is the t^{th} measurement point
- k is a range incrementer such that $t-k$ gives the range over which the ITER is calculated

Percent-transfer, the TER, and the CTER are thus seen to be special cases of the ITER as formulated in equation (5). A measure attributable to Diehl and Ryan (ref. 3), which they call the flight substitution ratio, is also a special case of the ITER.

RELATIONSHIP BETWEEN THE GENERAL LINEAR MODEL AND THE SUBSTITUTION RATIO

The general form of the model relating performance Y to training factors can be given by the general linear model

$$Y = \mu_0 + \beta_1 X_1 + \beta_2 X_2 + \dots \beta_n X_n + e \quad (6)$$

where

- X_1, X_2, \dots, X_n represent training factors at coded levels, and may include combinations of training factors in the case of nonlinear or nonadditive relationships (e.g., $X_n = X_{n-1}^2$; $X_n = X_{n-1} (X_{n-2})$)
- $\beta_i, i = 1, n$ are coefficients that relate the factors to performance
- μ_0 is the intercept with the y-axis at the origin
- e is the error or difference between the fitted model and the data

We have been primarily considering the case of two input factors or training factors X_1 and X_2 , one of which is also the transfer factor. We have been designating the transfer factor as X_2 and will henceforth label it X_T for clarity. Thus, to model this relationship we first entertain the model

$$Y = \mu_0 + \beta_1 X_1 + \beta_T X_T + e \quad (7)$$

We have earlier indicated that the theory of diminishing returns will often be in effect with regard to continued training on training factors. As a result, it is almost certainly the case that we will require additional polynomials of the training factors to model the relationships, but this consideration is set aside for the moment.

In cost-effectiveness analysis we are interested in relating the utilization of the transfer factor X_T to the training factor X_1 . As described previously, we can do this if we know or can estimate the equal performance contours of the response surface that results from the various combinations of X_T and X_1 . Under conditions of equal performance, the Y values of equation (7) become a constant. Thus,

$$Y_k = \mu_0 + \beta_1 X_1 + \beta_T X_T + e \quad (8)$$

where Y_k represents constant values of Y at some level k . We may then write,

$$-\beta_T X_T = \mu_0 - Y_k + \beta_1 X_1 + e \quad (9)$$

Since Y_k is a constant, its addition to or subtraction from the equation does not affect the estimation of parameters or the form of the relationship between X_1 and X_T . If the form of the relationship between X_T and X_1 is typically a negatively decelerated one, then we must posit the addition of a polynomial term or terms to the model of equation (9). Note that if model (9) were to stand, the relationship would be a simple linear one, and the substitution ratio would be a constant. Adding square and cubic terms we have

$$-\beta_T X_T = \mu_0 + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_1^3 + e \quad (10)$$

where $\mu_0 = \mu_0 - Y_k$. It is believed that equation (10) may adequately represent the relationship between X_T and X_1 . Other models could also be proposed to represent this relationship. In particular, one might posit an exponential-decay-type model to express the diminishing-returns assumption directly. The exponential-decay model has some advantages and will also be developed. However, representing the relationship as a form of the general linear model also has advantages, primarily its ease of use with readily available standard regression programs.

Now since we wish to relate X_1 to unweighted units of $X_T - \beta_T = 1$. Thus

$$X_T = \mu_0 + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_1^3 + e \quad (11)$$

and we have a model that expresses performance in terms of the relationship between the transfer factor and a training factor. The differential of equation (11) with respect to X_1 gives the substitution ratio at X_1 . The model can easily be expanded to include additional training factors as necessary.

The sequence from equation (6) to (11) illustrates the mathematical rationale for relating the transfer and training factors under the equal performance condition. It also provides a mathematical rationale for measuring training effectiveness in terms of trials or of the time to reach criteria on the transfer task. Doing so, conveniently constrains the results to equal performance, and allows the results to be expressed in terms of the relationship between transfer and training factors. It should be noted that model (11) is specific to the level of performance that has been defined during measurement as the criterion. In theory, there is a model (11) for each level of performance, and the relationships described by the model may be different for different levels of performance.

The most likely alternative to the general linear model for these kinds of data would be the exponential decay function, which for a single parameter takes the form

$$X_T = \beta_0 \exp \beta_1 X_1 \quad (12)$$

where β_0 is the amount of X_T training required when $X_1 = 0$.

The addition of a constant c completes the model. (As written in eq. (12), c is assumed to be 0.) The constant c merely shifts the model up or down on the ordinate and does not affect the form of the relationship. A finite value of c represents that value of X_1 beyond which no further savings in X_T occurs. In this case the amount of X_T training required when $X_1 = 0$ is also estimated by $\beta_0 + c$.

This model is nonlinear because it cannot be written in a form that is linear in the parameters, that is, a model in which the X_n are known for each measurement and are not functions of the B_n . There are some advantages to this type of model, one of which is increased parsimony. For example, fitting this model to data would involve the estimation of three parameters rather than the four required when a cubic regression model is fitted to the data. If estimates of β_0 or c or both are available from the data, and if these are then fixed, only one or two parameter estimates are required when fitting the model. Another advantage is that this model expresses the assumption of diminishing returns directly. Thus it implies something of the nature of the relationship which may be desirable and useful, particularly when limited information regarding the empirical relationship is available. The use of this model will be explored and considered in more detail in the illustrations that follow.

Bickley derived this model analytically as a model suitable for cost-effectiveness analysis and used it successfully in studying transfer from a simulator to the AH-1 helicopter with application to a number of tasks (ref. 4). He derived the model by noting that under the diminishing-returns assumption, it is reasonable to assume that as X_1 increases, the

rate at which X_T decreases is a constant proportion of $X_T - c$. This relationship can be represented as a linear differential equation which, when solved, yields the solution in equation (12).

OPTIMAL COST-EFFECTIVENESS

It has been shown that the point of optimal cost-effectiveness for a given level of performance is that point at which the ratio of costs for the training and transfer factors is equal to the substitution ratio for the factors. If the form of the relationship between factors is represented by a model such as (11), the model may be differentiated with respect to the training factor to determine the rate of substitution at a specific level of training factor. Differentiating equation (11) gives

$$\frac{d(X_T)}{dX_1} = \beta_1 + 2\beta_2 X_1 + 3\beta_3 X_1^2 \quad (13)$$

and differentiating equation (12) gives

$$\frac{d(X_T)}{dX_1} = \beta_0 \beta_1 \exp \beta_1 X_1 \quad (14)$$

These expressions are simply continuous forms of the ITER given in equation (5). If the measurements "t" referred to in equation (5) are taken in suitably small increments and if k is 1, the ITER function approximates the differential functions.

Assuming that the ratio of unit costs of the training factors is constant, we need only set that ratio equal to the differential function and solve for X_1 , which will give the point of optimal training effectiveness. The cost ratio is given by the slope of the budget-constraint line. Thus,

$$C_{SL} = \beta_1 + 2\beta_2 X_1 + 3\beta_3 X_1^2 \quad (15)$$

and for the exponential decay model,

$$C_{SL} = \beta_0 \beta_1 \exp \beta_1 X_1 \quad (16)$$

where C_{SL} is the slope of the budget-constraint line.

Thus, if the form of the relationship between the transfer and training factors is known, or if it can be estimated from data, and if the costs per unit of the factors are known, computation of the optimal cost-effectiveness point is a relatively simple matter; it is accomplished by solving either equation (15) or (16) for X_1 . Equation (15) is solved by the use of the quadratic formula. (There will be two values that satisfy the equation,

but only one will apply under normal conditions.) The solution for the exponential decay model is

$$X_1 = [\ln(C_{SL} / b_0 b_1)] / b_1 \quad (17)$$

where b_0 and b_1 are estimates of β_0 and β_1 , respectively.

The slope C_{SL} is equal to $-C_1/C_T$ where C_1 is the cost of a unit (such as an hour) of the training factor, and C_T is the cost of a unit of the transfer factor. In terms of the ITER,

$$\frac{C_1}{C_T} = \frac{X_{T,t-1} - X_{T,t}}{X_{1,t} - X_{1,t-1}} \quad (18)$$

within the *increment* of optimal cost-effectiveness.

Simplification of the Exponential Decay Model

The exponential decay model may be transformed to simplify it into a linear form. Taking natural logarithms of equation (12) we have

$$\ln(X_T - c) = \ln \beta_0 + \beta_1 X_1 \quad (19)$$

which is in the form of the general linear model if we set $X_T = \ln(X_T - c)$ and $\beta_0 = \ln \beta_0$:

$$\dot{X}_T = \dot{\beta}_0 + \beta_1 X_1 \quad (20)$$

The use of this simplified model does require an independent estimate of the value of c (the point beyond which there is no additional savings in the aircraft training), and this value must be subtracted from the X_T values before the transformation is made. When the model is fitted with a regression program, the estimated values b_0 and b_1 will be obtained. The natural antilog of b_0 is then taken to give β_0 , and the values b_0 and b_1 may be entered into equation (17) to solve for the point of optimal cost-effectiveness. Note that equation (20) itself cannot be solved algebraically for the point of optimal cost-effectiveness since the differential yields a constant. However, it could be solved by means of numerical methods by using the model to predict the performance isoquant in values transformed back to the original scale. The estimate of the value of c can be problematical. It must be constrained such that $(X_T - c) > 0$ for all values of X_T , and probably should be constrained such that $(X_T - c) \geq 0.05$, the latter in order to keep the model within realistic bounds. It should be noted that modeling will not work well when the data do not show reasonable evidence of stability or, in the case of the exponential decay model, if they do not show reasonable evidence of diminishing returns within the range of interest. In these cases, one should not go beyond the data in attempting to determine the point of optimal cost-effectiveness.

A Hypothetical Experiment

Suppose that an experiment has been performed with data collected at 15 combinations of X_T and X_1 with the results shown in table 3. (In practice, of course, there would generally be only three or four of these combinations available.) The data shown in table 3 are plotted in figure 4. These results show the characteristics expected under the diminishing-returns assumption, that is, as more hours of simulator time are added, there is proportionately less savings in aircraft time. The ITER's for these data are also given in table 3, giving the *average* substitution ratio over the 1-hour simulator increment.

Table 3. Sample Data for Hypothetical Experiment

t^a	Aircraft X_T , hr	Simulator X_1 , hr	ITER ^b
1	8.20	0	
2	6.40	1	1.80
3	5.00	2	1.40
4	4.10	3	0.90
5	3.20	4	0.90
6	2.60	5	0.60
7	2.00	6	0.60
8	1.60	7	0.40
9	1.40	8	0.20
10	1.20	9	0.20
11	1.10	10	0.10
12	1.00	11	0.10
13	0.90	12	0.10
14	0.85	13	0.05
15	0.80	14	0.05

^a t denotes the t^{th} measurement combination.

^b Incremental transfer effectiveness ratio.

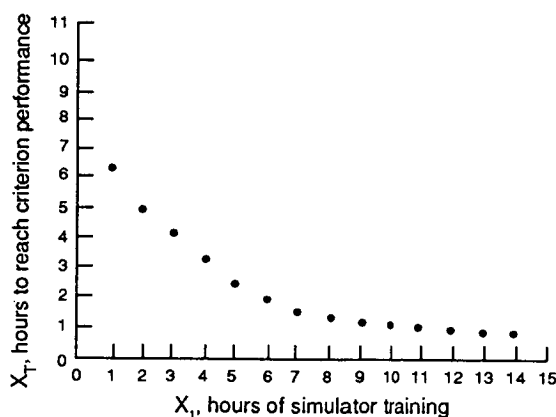


Figure 4. Plot of sample data given in table 3.

Assume that simulator time costs \$100/hr and that aircraft training time costs \$150/hr. Then the slope of any budget-constraint line is given by

$$(-100/150) = -0.67$$

and the point of optimal cost-effectiveness is given by the point at which the substitution ratio is equal to the cost ratio. In terms of the ITER, the sign of the budget-constraint line is reversed, and it can be seen in table 3 that the value 0.67 lies in the increment from 4 to 5 hours of simulator time. If the aircraft cost 4 times as much as the simulator per hour, giving a cost ratio of 0.25, the optimal cost-effectiveness point would lie in the increment from 7 to 8 hours of simulator time. It should be noted that in this example incremental transfer effectiveness is greater than 1.0 for the first 2 hours in the simulator. This is not merely hypothetical: training on a high-level simulator that fully supports the training task may be more efficient than training in the aircraft if, for example, more trials per hour can be run in the simulator, or if instructional strategies used during simulator training result in increased efficiency (see, for example, ref. 5).

A Real World Example

It is unlikely that in practice data would be available at the level of detail given in table 3. It is much more likely that data would be available at only a few of the levels given in the earlier example, and we would simply not know whether the range of data available covers the range of interest. If the data came as the result of a single historical change, there would be data available on only two combinations of training factors. In practice then, our ability to model the data to the point of being able to accurately estimate the point of optimal cost-effectiveness would be severely restricted. In the case of only two training factor combinations, "modeling" breaks down into a simple comparison of the alternatives.

One of the best examples of a transfer-of-training experiment that provides data that can be used to determine optimal use of a flight simulator is attributable to Povenmire and Roscoe (ref. 5). (Bickley also provides excellent data and utilizes this method (ref. 4).) The data also provide an example of diminishing returns in practice. In the experiment, students trained for 0 (control), 3, 7, and 11 hours in the simulator and then were trained to criterion in the aircraft. The results are plotted in figure 5. These data were fitted to the exponential decay model by Bickley (ref. 4), which resulted in the following estimated model:

$$X_T = 6.7 \exp(-0.397X_1) + 37.6$$

This information tells us that 44.3 hours are required, on average, in the aircraft to reach the criterion ($6.7 + 37.6$) when there is no simulator training; that 37.6 hours of aircraft training are required even if a very large number of simulator hours are run, and that the maximum number of aircraft training hours that can be saved by simulator training is 6.7. Differentiating gives

$$\frac{d(X_T)}{dX_1} = 6.7 (-0.397) \exp (-0.397 X_1)$$

Setting the result equal to the ratio of costs and solving for X_1 ,

$$X_1 = \ln [(-C_1/C_T) / (-2.66)] / (-0.397)$$

Thus, if the cost of the aircraft is twice that of the simulator ($C_1/C_T = 0.05$), then $X_1 = 4.2$ hours, the point of optimal cost-effectiveness. If the aircraft cost per hour is 10 times that of the simulator per hour, then $X_1 = 8.3$ hours, etc.

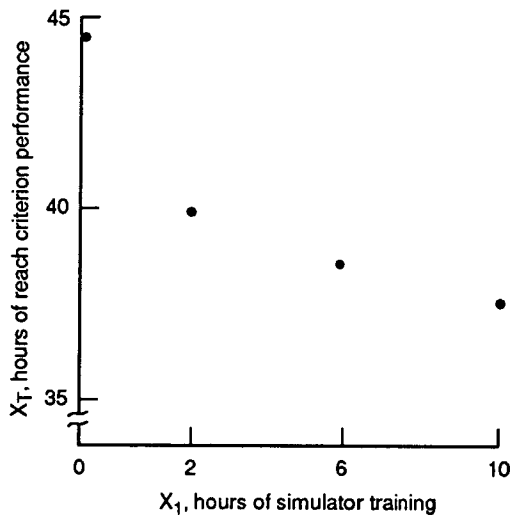


Figure 5. Plot of data given in Povenmire and Roscoe (ref. 5).

It should be noted that the methods described here are applicable to multiple levels of a training program. For example, they may be used to determine the optimal use of a part-task trainer, of a procedures trainer, or of computer-based training. In the case of computer-based training, the methods could be used to determine the optimal use in place of academic training or procedural training or both.

Types of Prediction Models

In theory, a variety of prediction models could be used to model the relationship between training and transfer factors. The general linear model is attractive because of the availability of computer programs and the relative ease in fitting the model. Another advantage is that the model is easily expandable to include multiple training factors. The exponential model is also expandable, but not so easily. The disadvantages are that if a cubic model is required, four data points are required to fit the model (three for a quadratic

model), whereas only three are required for the decay model if β_0 can be estimated separately and fixed. (This is strongly recommended, and in this case set $\beta_0 = \hat{\beta}_0 - c$ when fitting the model where $\hat{\beta}_0$ is the estimate of time to criterion on the transfer factor when there is no simulator training.) The exponential model is definitely preferable theoretically, for it directly expresses the diminishing-returns assumption. Although not as readily available, computer programs are in common use for fitting nonlinear models (e.g., ref. 6). The exponential model is also likely to perform better at the limits of the ranges of the data. The presence in the general linear model of higher-order terms, which accelerate rapidly, tends to make the model unstable near the limits of the range.

Limitations of Prediction Models

Models that are derived by fitting obtained data are no better than the data that are available. Thus, all the flaws that may be present in the data in terms of inaccuracies and confounding will also be present in the model. Generally, models that have been fitted to obtained data predict performance within the range of the obtained data much better than they predict performance outside the range. Caution must also be exercised with the decay model when the estimated values of β_1 become very large. This happens, for example, when the training time data are flat, which results in the fitting of a "square" curve. For example, if the data showed that 6 hours of aircraft time had been saved after 10 hours in the simulator, and that no further savings accrued after 15 and 20 hours, use of the decay model would predict that most of the savings had been realized very quickly. However, we have no information about the function between 1 and 10 simulator trials, and this is where the "action" is occurring in terms of the functional relationship. In this case, more data would be suggested rather than dependence on the model. Bickley gives several examples of this occurring with real data for the AH-1 helicopter simulator (ref. 4).

COMPREHENSIVE EVALUATION OF SIMULATION COST-EFFECTIVENESS

In a modern flight simulator there are many systems and subsystems or elements (factors, in experimental design terms) that affect the cost of the simulation, as well as the fidelity, both physical and functional, of the total simulation. There are also generally a number of tasks taught in the simulator that may or may not have overlapping task elements, and that may transfer to the real task in varying degrees. The issues of multiple tasks and multiple simulator factors require separate consideration. Performance is generally task specific, so tasks must be considered individually. Bickley did this for the AH-1 helicopter flight simulator and found that transfer of training ranged from near zero to near 100% for a variety of tasks. An optimal amount of simulator training time should be computed for each distinct task; the total optimized training cost for all tasks is then simply the sum of the costs for each task that is taught and trained.

It is helpful to distinguish between cost-effective use of a simulator and cost-effective simulation. The preceding material deals with the determination of cost-effective

simulator use, given a specific simulator, although simulator design features could be included in the cost-effectiveness analysis model. However, in terms of cost-effective simulation, the many possible design factors are better considered under the strategy defined below. A cost-effective simulation may be described as a simulation that provides the cues and feedback that are necessary to support training for a particular task or set of tasks at the lowest cost. Note that in some instances it may be possible to enhance or augment specific cues and to get the same or even better effect than by utilizing more expensive display options.

The issue of the multiple simulator factors that affect performance, training, transfer, and ultimately cost-effectiveness is not so easy to deal with. Conducting a large number of transfer-of-training experiments for a variety of simulator factors is generally impractical. Time and cost would make such an approach prohibitive. However, approaches have been suggested that provide for economic experimental evaluation of a number of simulator factors. In particular, Westra et al. propose a three-phase process for determining cost-effective simulation and training (ref. 7). The three phases involve performance experiments, in-simulator transfer-of-training experiments, and true (field) transfer-of-training experiments. Each phase serves as a screening function for the following one and makes use of economical multifactor design strategies to whatever extent possible. Figure 6 presents this strategy in flowchart form.

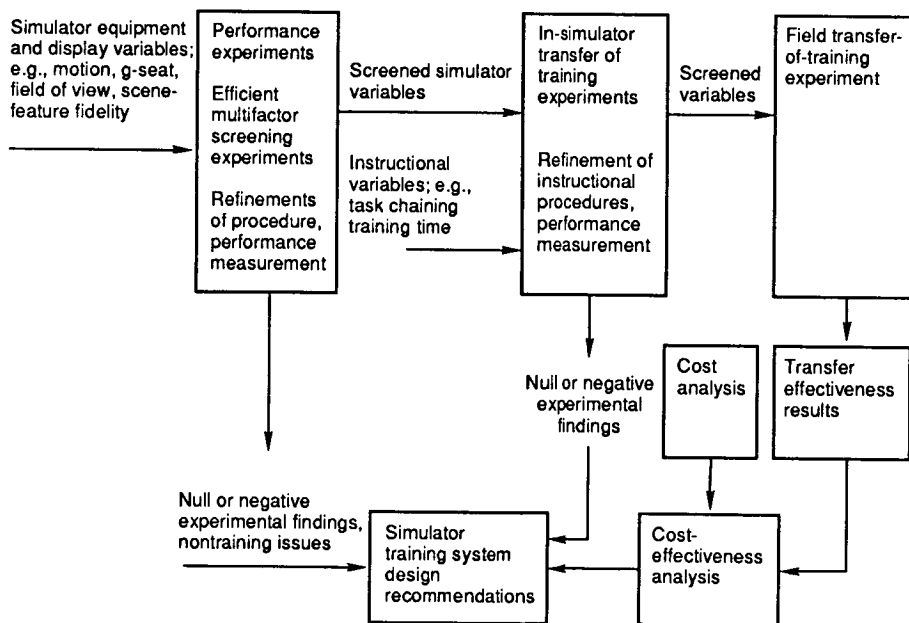


Figure 6. Summary of research program to efficiently obtain experimental results for simulator training system design.

Performance Experiments

Performance experiments do not involve the transfer-of-training paradigm; instead they involve the testing of experienced pilots in the simulator under various design conditions or options. Generally, these conditions and options are cast in the form of simulator factors that are set at two levels, one low and one high, that usually represent differences in fidelity and cost. The low level then represents a relatively low-cost alternative but one within a feasible range that may be the level in a current operational flight trainer. The high level of the factor is usually an enhanced or higher cost version. For example, for the visual factor TV line rate, the low level and lower cost version would be the standard 525-line rate available with off-the-shelf components, and the high level might be a much more expensive 1025-line rate visual display. The higher line rate would give higher resolution, but that level of resolution might not be necessary to support the required performance or training. In this case a null finding at this stage would eliminate the factor from further consideration. On the other hand, a positive finding would indicate that the factor should be studied further, perhaps with a third level to further define the performance function.

Performance experiments are much cheaper to conduct than transfer-of-training experiments, particularly if within-subject designs are utilized. They are also well suited for the application of economical multifactor experimental designs so that a properly conducted experiment can yield a wealth of information at relatively low research cost. The use of performance experiments as screening devices does require a key assumption: factors that make no difference on performance in the simulator will not make a difference in transfer of training. This assumption is reasonable and is generally supported by the results of studies reported in the literature, although there are exceptions. If there is any question, a very high cost factor, such as a motion platform, should also be included in the next stage of research, even if the effect on performance is nil.

Another advantage of performance experiments is that performance does not need to be held equal in order to make initial screening judgments regarding the cost-effectiveness of various similar design factors. Thus the experimental model is the usual general linear model (e.g., (6)), which relates performance to the experimental factors. This allows a much simpler and direct expression of the effects, compared with the non-linear exponential decay model, when determining optimal cost-effective use of the simulator, although the equation (6) model itself can get quite complicated when multifactor designs are used. A final and important consideration in the use of performance experiments is that they may be viewed as a form of backward transfer when experienced pilots are used. Cross discusses this idea at length and notes that in this perspective, results can be used not only to screen factors for transfer-of-training experiments, but to determine simulator problem areas (ref. 8). This generates a great deal of information for use in determining what needs to be done to improve simulation in those areas where there appear to be shortcomings in simulator support for training real-world tasks.

In-Simulator Transfer-of-Training Experiments

In-simulator transfer-of-training experiments are recommended for the second stage of the research process to determine the cost-effectiveness of simulation and training.

In these types of experiments, which utilize the transfer-of-training paradigm, pilots new to the task are trained in the simulator under various conditions, and then tested under a high-fidelity test condition in the simulator. This stage is more expensive to conduct than performance experiments, since within-subject designs cannot be used, but still costs less than experiments involving testing in the aircraft. Economical multifactor designs can also be used to hold down the cost of research while yielding a great deal of information. In this stage also it is not necessary to hold performance equal (train to criterion) in the transfer test phase in order to make decisions about the effect of these factors.

There are a number of other arguments in favor of these kinds of experiments, although it must be noted that they are useful only if it is assumed that simulator training will have a positive transfer to the aircraft. Generally, this is a reasonable assumption, considering the wealth of data that show the positive benefits of simulator training. In-simulator experiments can be used to further screen variables and to define levels of variables for field experiments. Experimental control is better in the simulator, and the extent to which performance can be measured in the simulator is virtually unlimited; on the other hand, many performance measurements can be difficult or even impossible to make in the aircraft. Another major advantage of in-simulator experiments is that instructional methods or factors can be investigated in a relatively low-cost manner. Instructional issues have proved to be important in the use of the simulator. This is even more important when it is considered that instructional techniques that enhance training may often be incorporated into the training system at little or no cost. Advantageous instructional methods may maintain the level of transfer effectiveness or even enhance transfer effectiveness while reducing simulator training time. Backward-chaining for the aircraft carrier landing task is an example of this (refs. 9, 10).

Field Transfer-of-Training Experiments

The final phase of the research process of determining optimal training cost-effectiveness involves a field transfer-of-training experiment. This of course involves the traditional transfer-of-training paradigm which is the subject of the initial section of this chapter. It is this final phase that determines the bottom line for simulator design, instruction, use, and cost issues. It should be noted here that it is not strictly necessary to use training-to-criterion as a performance measurement method in order to determine the optimal cost-effective use of the simulator. However, if this is not done, that is, if the subjects perform a fixed number of trials in the aircraft, it must be made certain that the subjects will achieve the criterion in the fixed number of trials, and that there is an accepted method for determining when the criterion has been reached. Using a fixed number of trials under these conditions is actually preferable to using trails-to-criteria. The data will not only contain information necessary to determine the optimal cost-effective use of the simulator, but will contain additional performance data which will allow a more sensitive and detailed investigation of transfer performance, irrespective of costs.

Economic Multifactor Design

It is beyond the scope of this chapter to present the mathematical and logical bases for the economy that is achieved when the procedures advocated by Simon (refs. 11, 12), and others (refs. 13-15) are followed. However, a very brief discussion of some of the key

ideas and methods is in order, for there is no other economical means of investigating a large number of factors, and the research economy that can be achieved is remarkable. The process involves the use of a collection of procedures and tools that proceed from an initial screening of all the factors of interest to the definition of response surfaces. It should be noted that the word *screening* in this context has a different meaning than it does in the three-phase process presented above. In that situation, screening refers to the process of considering variables for inclusion in the transfer-of-training experiments. In this situation, screening refers to the process of considering variables for inclusion in the next step of the process to define the complete response-surface relating performance to experimental variables. It is in the screening phase that the greatest economy can be obtained through the use of fractional factorial experimental plans, particularly if the number of factors to be investigated is large.

In the context of the three-phase program defined above, an initial multifactor fractional factorial performance experiment may provide most or all of the information necessary to move on to the transfer-of-training phase. In this respect, the primary tool for executing a screening design is a carefully selected fraction of a full factorial. For example, consider the case of 11 factors whose influence on the training process we wish to investigate (11 factors would not be an unusually large number for a full mission flight simulator). Execution of a full factorial for this situation would require 2,048 conditions if each factor is set at two levels. However, much of the information obtained would be on the higher-order interactions, most of which would be negligible. On the other hand, we could select 64 of these conditions (1/32 of the full factorial) in such a way that all 11 main effects could be estimated independently, both of each other and of two-way interactions (ref. 14). Under the assumption that three-way and higher-order interactions are negligible, all the main effects and two-way interaction strings could be eliminated. Such a design is feasible, particularly within the context of a within-subject performance experiment.

There are benefits to be derived from a design like this that are in addition to the potentially large gain in economy. The results are more generalizable because they have been obtained across a wide range of conditions. Most estimates of effects are free of contamination from most within-subject trend or learning effects as an inherent characteristic of the design (refs. 16, 17). Another beneficial result is that an ordered list of factor effects is obtained. This result is useful in determining the operational significance of effects and, typically, provides information that is difficult if not impossible to construct when a number of separate experiments are performed. This is because different experiments are rarely done under the same conditions. When relative magnitudes of the effects obtained in the same context are seen along with the percent-variance-accounted-for in a situation in which the important factors that influence performance are operating, a much more accurate indication of the practical significance of the effect is obtained.

Examples of the Method

The progression through performance, quasi-transfer, and transfer studies, and the use of economical multifactor designs are independent research strategies that have been com-

bined in flight simulation research. Westra used a fractional factorial design to examine six simulator factors, including scene type, in a performance study of air-to-ground attack (ref. 18). Scene type had a significant performance effect. The study reported in reference 18 was followed by a quasi-transfer-to-training experiment by Lintern et al. in which scene content was again shown to be important (ref. 19). The final study in this series was a transfer study in which there was no evidence of a scene-content effect, but in which there was evidence of positive transfer (ref. 20). The data from the transfer study, which provided the final test of scene type, led to the conclusion that minimally detailed scenes resulted in substantial transfer-of-training for this task. In addition, this experiment showed that the most substantial transfer gains were produced by the first 24 training runs on the bombing task, and that there was relatively little benefit from further simulator training.

A similar strategy has been used to examine the effectiveness of different simulator features for teaching landings to beginning flight students. Lintern et al. (ref. 21) and Lintern and Koonce (ref. 22) used multifactor designs to examine quasi-transfer effects. The factors tested in those studies were selected on the basis of performance studies reported by others, thus avoiding the need for the first step. Scene-content and augmented information factors showed significant quasi-transfer effects. Scene content was subsequently shown to have an effect on transfer (Lintern, G.; et al.: *Transfer and Quasi-Transfer Effects of Scene Detail and Visual Augmentation in Landing Training*. Submitted to *Human Factors*, 1994). Again, in this series of studies, the progression through performance, quasi-transfer, and transfer studies that incorporated the multifactor designs led to important conclusions about the simulator design features that facilitated training transfer.

Costs

It has been generally assumed throughout that cost data would be provided to the researcher conducting the analysis, and it is beyond the scope of our purpose here to consider the matter of costs in detail. However, we would be remiss if we failed to mention that cost analysis can be a very complex matter when the systems involved are complex. This was illustrated by String and Orlansky who cited widely varying rates — \$418 to \$2284 per hour — from five different sources for the cost of training in the P-3C aircraft (ref. 23). Issues such as constant dollars (adjusted for inflation), life cycles of the equipment, development costs, and the time-value of money all may enter into cost computations. In general, costs need to be described in sufficient detail so that all significant cost drivers are identified. A systematic and detailed cost-element structure has been proposed for military training systems (ref. 24). Finally, it should be noted that there are cost items besides simulator and aircraft costs that should be considered in a thorough cost analysis. For example, in a given case it may be that use of the simulator reduces student washout and washback rates even though it does not reduce the number of training hours in the aircraft.

CONCLUSIONS

Simulation cost-effectiveness and simulator use can be evaluated efficiently by using the methods described and illustrated here. The use of an exponential decay function is

recommended to model the transfer function relating training and transfer factors. If the cost per unit time of these factors is known, then the optimal use of the simulator can be determined. A three-phase evaluation process can be used to efficiently evaluate simulation cost-effectiveness, starting with performance experiments, followed by in-simulator transfer-of-training experiments, and finally by field transfer-of-training experiments in which the optimal use of the simulator is also determined.

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5 THE MILITARY QUEST FOR FLIGHT TRAINING EFFECTIVENESS

Jack Dohme*

SUMMARY

The military approach to vertical flight training is defined by the demanding characteristics of rotary-wing missions and by the scope of the related training requirements. The military training environment takes an individual off the street and inculcates the fundamental and advanced skills necessary to pilot a complex helicopter. But the greater challenge follows that initial training: training the aviator to survive while effectively employing the aircraft in a hostile environment. Instructing large numbers of individuals who graduate from flight school ready to fly under combat conditions demands excellence in training. Maintaining that excellence in training requires frequent evaluation and revision of the training curriculum and training materials in order to cope with the training demands imposed by increasingly complex aircraft and increasingly demanding missions. This chapter provides an overview of the challenge to maintain military rotary-wing training effectiveness and of research efforts to enhance and improve the quality of that training.

INTRODUCTION

The U.S. Army is unique in the flight training business. Since the Viet Nam era, all Army ab initio flight training has been rotary-wing training in the Initial Entry Rotary Wing (IERW) course at Fort Rucker, Alabama. In recent years, there have been about 12,000 applicants each year for the IERW course, and each year about 1,500 aviators (including U.S. Air Force and allied nation pilots) have been graduated. Most of the U.S. Army applicants have no prior flight training and only limited prior exposure to the world of aviation. I am aware of more than one IERW trainee who has arrived at Fort Rucker without a driver's license or with any experience in the operation of any kind of vehicle. Moreover, the high cost of military flight training (e.g., \$212,463 in FY93 dollars per UH-1 helicopter-track IERW graduate) and the total number of rotary-wing hours flown in support of Army aviation (averaging 1.4 million hr/year from FY84-93) drive the requirement for efficiency in the training system.

A comparison of civilian and military rotary-wing training statistics shows that the U.S. Army Aviation Center (USAAVNC) at Fort Rucker is the largest "helicopter

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pilot factory” in the Western world. In fact, the annual number of rotary-wing trainees at Fort Rucker rivals that of the rest of the U.S. training community combined. The average annual number of graduates mentioned above (about 1,500) includes an average of 22 U.S. Air Force trainees per year. By contrast, the average yearly number of Army trainees acquiring fixed-wing (f/w) ratings was six.

Flight training statistics from the Federal Aviation Administration (FAA) reveal that an average of 2,296 individuals per year earned an original civilian rotary-wing rating over FY88-90, when Fort Rucker was averaging 1487. However, since Army IERW graduates need only pass a short written examination on the Federal Aviation Regulations (FARs) to qualify for a commercial instrument rotorcraft helicopter rating, this number of civilian licenses also includes military trainees who opted to take the examination and to obtain a civilian rating in addition to their military rotary-wing rating. (FAA statistics are not available for the number of trainees taking the FAR examination to obtain a civilian rotary-wing rating nor does the Army maintain data on the number of trainees who pursue this rating on their own time. The author’s estimate is based on several classes of IERW trainees.) The percentage of IERW graduates taking the FAR examination varies over time but averages about 60%. Therefore, about 1,378 of the 2,296 civilian-rated pilots in the FAA statistics are actually Army trainees receiving additional civilian ratings. These figures imply that approximately 2,415 rotary-wing pilots received their initial ratings in each of the three target years and that the Army trained 62% of them.

These statistics constitute a challenge to develop a military rotary-wing training program that is effective, efficient, and responsive.

1. *Effective*: Graduates must acquire combat skills to survive on the battlefield and accomplish rotary-wing missions.
2. *Efficient*: Training costs must be kept as low as practical.
3. *Responsive*: There is a need to continually assess the quality of training and to implement changes as required to optimize training effectiveness and efficiency.

This chapter summarizes the efforts made by the military rotary-wing training community to meet the training challenge in a responsible manner. As trainers, we are responsible to the following:

1. Our students, to provide *effective* training
2. The taxpayer, to provide *efficient* training
3. The national defense, to provide *responsive* training

All of the players in the training community face this challenge and have the potential to contribute to excellence in training. Nonetheless, the primary responsibility falls on the human factors research practitioners because they hold the tools for empirically evaluat-

ing and improving training. In short, this chapter reviews the application of aviation human factors research to enhance the quality of military rotary-wing training.

TRAINEE SELECTION AND ASSIGNMENT: WHO'S BEING TRAINED?

The first requirement in the United States for large numbers of military aviators occurred in the early 1940s during the buildup for World War II. And as the numbers of pilot trainees increased, so did the attrition rates in flight training. The attrition problem became so acute that in the Army Air Forces only 100 trainees graduated of every 397 applicants accepted for (fixed-wing) flight school (ref. 1). The solution to this unacceptable attrition rate was the development of the Army Air Forces Qualifying Examination (AAFQE) in 1942 (ref. 2) and of the Aircrew Classification Battery (ACB) at the same time (ref. 3). The implementation of the AAFQE and the ACB cut the attrition rate in training from 75% to 35% (ref. 1). These efforts to improve training effectiveness through research led not only to routine screening of applicants for military flight training but also to the development of aviation human factors engineering in support of military flight training.

After World War II, the problem of unacceptable attrition rates in aviator training recurred (ref. 4). There appeared to be two changes in the training program that precipitated the increased attrition: (1) the introduction of rotary-wing aircraft into the military inventories and (2) the development of a specific training track for warrant officer candidate (WOC) aviator trainees. The WOC trainees, who were not college graduates, evidenced a particularly high attrition rate in training (ref. 4). Kaplan found the World War II selection tests to be ineffective as predictors of rotary-wing training performance (ref. 4). In 1955, researchers began to develop a battery of tests that would be simple to administer (unlike the apparatus-based ACB) but that would predict success in both fixed-wing and rotary-wing training. A timed pencil-and-paper instrument called the Flight Aptitude Selection Test (FAST) was published in 1966; it was published in two versions, one for officer applicants and the other for warrant officer candidate applicants. The newly developed FAST was found to be an effective predictor of failure owing to "flying deficiency" for both applicant groups (ref. 4).

The FAST has been revised twice, once in 1978, the Revised Flight Aptitude Selection Test (RFAST), and once in 1981, the Alternate Flight Aptitude Selection Test (AFAST). The AFAST was a further revision to the RFAST in that it evaluated the test for bias in the selection of minority applicants for flight training (ref. 5) and eliminated or replaced those items found to be biased either for or against minority applicants (ref. 6).

In practice, the AFAST is only one of the screens used to select trainees. In common with the civilian aviation community, motivation and self-selection play a role in determining who will apply to the program. And, in common with civilian rotary-wing training, the applicant must pass a flight physical examination (Class A in the case of military applicants). Before being allowed to sit for the AFAST, however, the Army WOC applicant must first take the Armed Services Vocational Aptitude Battery (ASVAB) and demonstrate a General Technical (GT) score of at least 110, corresponding to ap-

proximately the 65th percentile in the ASVAB population. The GT score is composed of three sections: arithmetic reasoning, word knowledge, and paragraph comprehension. Officer applicants are not required to take the ASVAB, the presumption being that as college graduates they have demonstrated the aptitude and motivation for successful academic performance. Both applicant groups are also qualitatively evaluated on additional criteria: (1) age, (2) experience, (3) field grade officer interview, (4) academic grades (high school and college), and (5) service grades (for prior enlisted applicants). Research has demonstrated that age is a powerful predictor of IERW training performance . . . and younger is better! There is a point of inflection in the late 20s where the probability of graduation begins to decline, falling to approximately 60% at or above age 36 (ref. 7).

The relative contributions of the objective screening measures to IERW training performance were evaluated by Dohme et al. (ref. 7). A discriminant analysis was performed using four screening variables as predictors of pass/fail in the IERW course: RFAST, GT, age, and years of education. The discriminant analysis correctly predicted graduation versus flight-deficiency elimination for 82% of the WOC trainees and for 86% of the officer trainees. (The technique, of course, did not predict eliminations for medical or administrative reasons.) However, virtually all of the predictive power was in the RFAST and age variables. Since all research subjects were preselected on the variables being evaluated, the range of scores in the trainee population was truncated, and the overall number of those eliminated was small. However, the research demonstrated that screening applicants for factors known to predict success in training can improve training completion rates.

Moreover, the research by Dohme et al. (ref. 7) demonstrated the difference between a screening test and a proficiency test. Since the GT score was used as a pretest to screen flight school applicants, the range of scores varied from 110 to over 150. Yet, applicants with scores from 110-119 had an 82% probability of graduating from the IERW program, whereas applicants with scores of 150 or greater had an 85% probability (see fig. 1). The practical conclusion is that once a screening test has performed its intended function, it does not improve training success to further use it as a predictor of order of merit in IERW training.

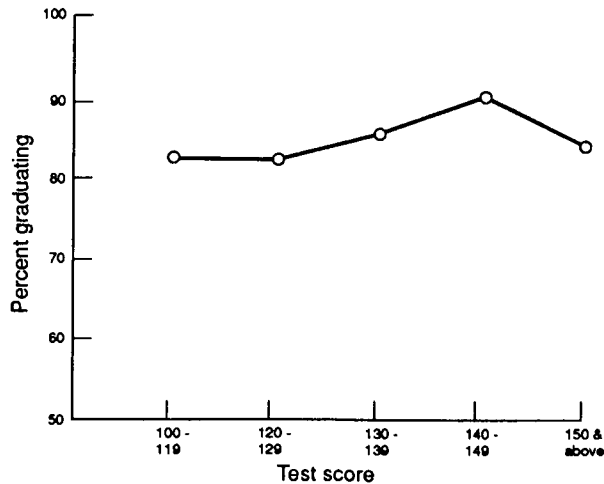


Figure 1. Graduation rate from IERW course for warrant office candidates: General Technical Test.

The value of an effective screening test in selecting students for rotary-wing training is corroborated by findings regarding the decision by the Department of the Army (DA) to lower the FAST "cut-score" during a 9-month period in FY80 and 81. The Military Personnel Center (MILPERCEN) was experiencing difficulty during that time in attracting sufficient WOC applicants to meet a surge in the demand for aviator training. The FAST cut-score was lowered from 300 points to 270 for WOC applicants (corresponding to a drop from just above the 50th percentile to about the 34th percentile). The Army Research Institute (ARI) recommended against the DA position because of an expectation of increased IERW attrition. When the decision was made to lower the cut-score, ARI took advantage of the opportunity to evaluate the efficiency of the FAST as a screening instrument.

The 200 plus WOCs accepted for training who had FAST scores between 270 and 300 were followed through IERW training. That group experienced a 37% attrition rate whereas the attrition rate for the group scoring at or above 300 was 14% (ref. 7). Figure 2 shows the relationship between trainee FAST scores and the percent graduating. The figure reveals that fewer than 60% of WOCs with scores below 279 completed training. The probability of course completion varies little over the FAST range of 310 to 360, but there is a clear point of drop-off below that range. Thus, the use of the test as a screening instrument was validated.

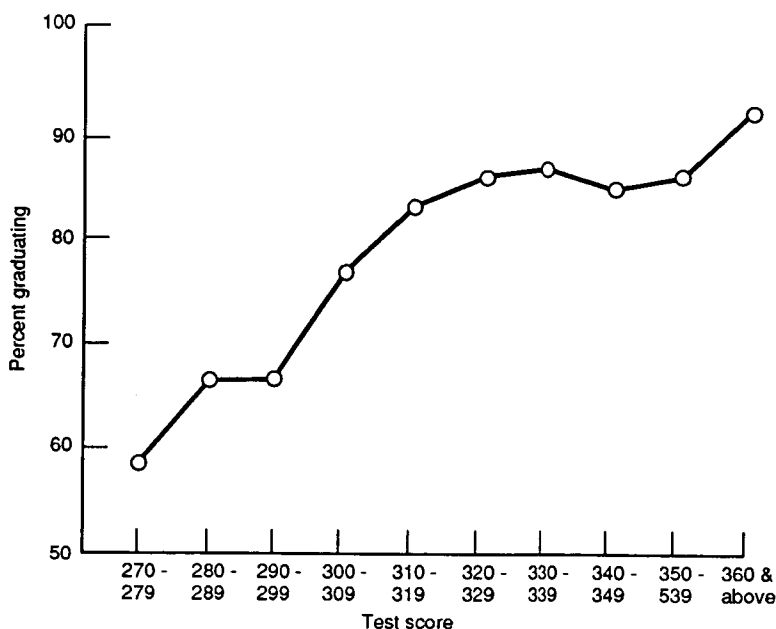


Figure 2. Graduation rate from IERW course for warrant officer candidates: Flight Aptitude Selection Test.

The overall goal of testing and screening is to increase the percentage of trainees graduating, and, hence, the efficiency, of the training program. Training failures and setbacks increase training costs and also adversely affect the career aspirations of the unsuccessful trainees. Given the high costs of military training and the large number of applicants, it has become essential to effectively test and screen applicants in order to increase the percentage of applicants who succeed. The use of the FAST variants, in conjunction with other screening criteria, has kept overall flight-deficiency attrition rates in IERW training well below 10% for both officer and warrant officer candidate trainees over the past decade. More recently, the IERW attrition rate for FY93 was 3.4% for commissioned officer trainees and 6.1% for warrant officer trainees for all causes. In both groups, the eliminations for reasons of flight-deficiency were less than 1.0%.

CLASSIFICATION FOR AIRCRAFT AND MISSION ASSIGNMENT

There is another possible application of testing in improving training efficiency: classification testing for mission and aircraft assignment. The goal of classification testing is to match trainee aptitudes, skills, knowledge, and interests with the operational requirements of the service. The first attempts at classification testing began with the previously mentioned Aircrew Classification Battery (ACB) during World War II. The ACB used portable apparatus to measure complex coordination, rotary pursuit, finger dexterity, discrimination reaction time, foot coordination, two-hand pursuit, and two-hand coordination (ref. 3). The test battery showed considerable promise in predicting success in specific mission training, for example, training for pilot, navigator, or bombardier. However, testing was discontinued after World War II because the apparatus of that period was unreliable and difficult to calibrate.

Currently, the Army, Navy, and Air Force all employ some means of "tracking" (or directing) flight students along paths that lead to certain mission-specific training programs. However, only the Army has an objective test battery and an automated assignment algorithm for this purpose. All of these assignment methods have elements in common because of the sharing of research findings and test designs among the military human factors community. The Armed Services Training and Personnel Systems Sciences and Technology Evaluation Management Committee (TAPSTEM) was formed to ensure cooperative utilization of research resources. This tri-service organization was developed in 1991 to fulfill four objectives:

1. Increase effectiveness and efficiency in service resource utilization
2. Address roles and organization and function issues across the services
3. Ensure relevance and reduce duplication through the review process
4. Define issues for resolution and coordination beyond TAPSTEM

With TAPSTEM, the Pilot Selection Special Topic Group (PSSTG) was formed. Its membership is made up of active researchers at the Army Research Institute Aviation

Research and Development Activity (ARIARDA), the Naval Aerospace Medicine Research Laboratory (NAMRL) at Pensacola, Florida, and the Air Force Armstrong Laboratory (AL) at Brooks AFB in San Antonio, Texas. The PSSTG is chartered to do the following:

1. Catalog similarities and differences in aircrew selection and classification research and development (R & D) programs
2. Review existing R & D programs
3. Determine cross-service applicability of new and existing programs
4. Explore methods to enhance tri-service synergy
5. Obviate duplicate efforts
6. Define issues beyond the control of TAPSTEM

The PSSTG group is currently pursuing these objectives, its goal being to improve the processes of selecting and classifying military aviators. The Army continues to serve as the lead agency for selecting and classifying rotary-wing trainees.

One specific example of the cooperative approach sponsored by PSSTG is the planned installation of six Air Force Basic Attributes Test (BAT) testing devices at USAAVNC. The BAT is a psychomotor/cognitive/perceptual test battery currently in use for selecting Air Force fixed-wing trainees. It includes subtests such as three-dimensional mental rotation, two-hand coordination, and time-sharing. The six devices being installed at Fort Rucker are experimental versions that will facilitate evaluation of new subtests for both fixed-wing and rotary-wing selection and assignment applications. All Army and Air Force IERW trainees will be tested to develop norms and to evaluate experimental BAT (EBAT) components for predictive validity as a selection or classification battery for both services.

Dual-Track IERW Training

The Army began differential assignment of trainees to IERW training tracks in FY77 with the onset of the "175/40" dual-track training program (it is reviewed later in this chapter). In the dual-track curriculum, officer and WOC trainees could earn their wings in either the Utility Mission or in the Aeroscout Mission. The primary Utility Mission, currently flown in UH-1 Huey or UH-60 helicopters, is to transport soldiers and supplies to support military objectives, for example, an "Airmobile" insertion of Army Rangers behind enemy lines. The primary Aeroscout Mission, currently flown in versions of the OH-58 Kiowa aircraft (and the OH-6 Cayuse in some National Guard units), is to perform reconnaissance on the battlefield, for example, to locate and identify enemy units and to orchestrate attacks on them. Early in the dual-track program, the elimination and setback rates for Aeroscout trainees was judged by the command group at Fort Rucker to

be excessive. The Aeroscout track was considered to be more rigorous and demanding than the utility track, but assignment to Aeroscout training was made based on the needs of the service and on the preferences of the trainees, not on trainee aptitudes. At that time, Aviation was not a combat branch of the Army, and mission assignment was often branch-related; for example, an armor branch officer would be assigned to an aeroscout or attack aircraft and a transportation branch officer would be assigned to a utility aircraft. The introduction of Aviation as a combat branch in FY84 solved many of these assignment problems.

Research was undertaken to determine whether trainees could be selected for assignment to Aeroscout training in order to improve training graduation rates. Dohme developed rating forms and administered them to 120 experienced aviators in the field to identify critical aptitudes and abilities in each mission (ref. 8). An assignment algorithm was developed from these subject matter expert (SME) inputs to assess Aeroscout abilities and aptitudes in trainees. Algorithm scores were then used to assign Aeroscout trainees (conjointly with trainee preference and the needs of the service) to improve the probability of completing the Aeroscout training regimen. The assumption behind this research effort was that the aptitudes and abilities, judged by the SMEs to be required for the Aeroscout mission in the field, would also be required for success in the Aeroscout training program at Fort Rucker.

The Aeroscout algorithm score was a composite of 11 weighted variables ranging from the most heavily weighted, Map Reading Skills, to the least weighted, Average Grade in Primary Training. The algorithm was validated against institutional and operational criteria. The institutional criteria consisted of grades in Aeroscout tactics in the training curriculum. Operational criteria were developed to evaluate Aeroscout track graduates after they left the institution and were flying the Aeroscout mission in the field. A Mission Proficiency Scale (MPS) was developed in cooperation with Army standardization instructor pilots (SIPs) by using a decision-tree model adapted from the Cooper-Harper aircraft handling-qualities scale (refs. 9, 10).

The institutional validation effort used a sample of 248 Aeroscout trainees as subjects. The algorithm score served as a predictor, and the combined Aeroscout tactics grades served as the criterion. The product-moment correlation was $r = 0.39$ ($p < .001$). The 11 algorithm components were subjected to a stepwise multiple regression analysis using the combined-tactics grade as the criterion; the multiple $R = 0.48$.

However, of greater importance was the operational validation, since the goal of training is to produce effective aviators in the field, not merely program graduates. When standardization instructor pilots (SIPs) from the Army's Directorate of Evaluation and Standardization (DES) went to the field to assess the combat readiness of field aviators, they were asked to evaluate recent IERW Aeroscout graduates using the MPS. Over a period of 6 months, only 15 evaluations were completed, but they demonstrated a correlation of $r = 0.57$ ($p < .05$) with the Aeroscout algorithm score serving as the predictor. A stepwise multiple regression of algorithm components with the MPS score yielded a value of $R = 0.71$.

Since a selection algorithm is basically a classification tool and not a screening instrument, the effectiveness of the technique can be evaluated by performing a discriminant analysis on the Aeroscout and Utility trainee samples. The discriminant analysis correctly classified 82.9% of the trainees into the Aeroscout or Utility groups ($n = 248$). It showed very few false negatives (Aeroscout trainees classified as Utility) but many false positives (Utility trainees classified as Aeroscout). This suggests that the abilities and aptitudes identified with Aeroscout success are also predictive of success along the Utility track, whether or not they are critical requirements of the Utility mission.

Overall, the Aeroscout validation effort led to four conclusions of importance to military training managers:

1. Selection of trainees for specific mission training could improve training efficiency and effectiveness.
2. A selection method based on SME judgments could successfully identify trainees who would have a greater probability of success in mission-specific training.
3. Selection for mission-specific training demonstrated validity against both institutional and operational criteria in the field.
4. The techniques required to develop and validate a practical mission-assignment algorithm were reasonable in cost and scope.

The Aeroscout algorithm was viewed by military managers and researchers as an interim step toward a full-fledged multi-track IERW training program. Based on the success of the Aeroscout algorithm, the Army began a research evaluation leading to multi-track training.

Multi-Track IERW Training

The multi-track IERW course was implemented in FY88 to reduce overall training costs. Before multi-track, transition training in advanced aircraft (all aircraft except the OH-58 and UH-1) was accomplished in follow-on Aviator Qualification Course (AQC) training. The goal of multi-track was to reduce the overall number of flight hours required to produce a mission-ready aviator; this was to be done by performing the mission-specific training within the IERW course in the advanced aircraft. For example, utility-track trainees would learn internal and external load operations, aeroscout trainees would learn aerial artillery adjustment skills, and attack trainees would learn target engagement skills.

The approach taken in the multi-track classification program was to develop and validate a battery of tests that would differentially predict training performance in each of the four training tracks: (1) UH-1 (Huey) Utility; (2) UH-60 (Blackhawk) Utility; (3) AH-1 (Cobra) Attack; and (4) OH-58 (Kiowa) Aeroscout.

(The correct Army name for the UH-1 is the Iroquois, but it is more widely known as the "Huey" because its original designation, the HU-1, was more or less pronounceable.)

A small-group analysis technique was used with 60 highly experienced Army instructor pilots (IPs) serving as subject matter experts (SMEs) to represent all six active Army rotary-wing aircraft (the UH-1, UH-60, AH-1, OH-58, CH-47, and AH-64). In six workshops, Linstone and Turoff used a modified Delphi technique to review the tasks and maneuvers published for each mission and aircraft in the Army Aircrew Training Manuals (ATMs) (ref. 11). The ATMs serve as the mission-requirements documents and, more important, the mission standards definitions for all Army aviation missions. All Army aviators are evaluated, at least once a year, in accordance with the ATM standards for their respective aircraft and mission. This evaluation includes written, oral, and flight objectives sampled from the ATMs.

The objective of the small-group analysis was to identify (1) those ATM tasks common to all Army helicopter missions and (2) those tasks unique to the operational success of each particular aircraft and mission (ref. 12). The ATM task lists were also rated in terms of the criticality of each task for operational success of the mission. Next, the critical ATM tasks were analyzed using Fleishman's taxonomic approach to identify and categorize the abilities underlying task performance (ref. 13). The categorization of abilities was subsequently validated by another group of instructor pilot SMEs.

A literature search, along with liaison with sister services and other agencies (FAA and NASA), identified candidate test instruments that could be used to assess the underlying performance abilities. The measures evaluated for the multi-track battery included the following:

1. The Basic Attributes Test from the USAF Armstrong Laboratory at Brooks AFB, Texas (ref. 14).
2. The Naval Aeromedical Research Laboratory (NAMRL) multi-tasking battery from Naval Air Station (NAS) Pensacola, Florida (ref. 15).
3. The NASA/Helmreich Cockpit Management Attitudes Questionnaire (CMAQ) (ref. 16).
4. The U.S. Army Research Institute Complex Cognitive Assessment Battery (CCAB), developed under contract by the EATON Corporation (ref. 17).

The 7-hour test battery was administered to 60 highly experienced Army instructor pilots, none of whom had participated in the small-group analysis. A stepwise multiple-discriminant analysis was performed to ascertain whether the UH-1, UH-60, AH-1, and OH-58 groups could be differentiated. The statistical procedure correctly categorized 97.5% of the instructor pilot (IP) group (ref. 12). However, differentiating experienced aviators in the field is far less demanding than differentiating low-time trainees in the IERW course. Thus, there was a requirement to experimentally test and validate the new multi-track test battery by using IERW trainees as research subjects.

USAAVNC at Fort Rucker made the decision to implement the experimental test battery and to use it for classification beginning in May 1988. All subsequent IERW trainees were tested with the battery, and data were tabulated on their performance in the IERW common core and in aircraft- and mission-specific training in the latter part of the 36-week training course.

The discriminant functions developed by Intano et al. (ref. 12) were used in conjunction with other selection factors (IP recommendations, trainee preference, performance of the trainee in the first 96 days of IERW training, anthropometric measurements, and sex of trainee) to assign students to training tracks. The administrative inclusion of these additional selection factors actually reduced the percentage of trainees who were assigned to their best or second best match (of track requirements with trainee ability) to approximately 55% (ref. 18). In other words, the discriminant functions alone were better at classification than were the combined administrative selection factors and the discriminant functions.

With more than 3,000 IERW trainees serving as research subjects, the multi-track classification technique showed considerable promise in tracking IERW trainees. Research results show that common-core grades were not particularly useful predictors of success in specific training tracks, with the exception of the UH-1 Utility track. The latter is considered an artifact, because the UH-1 aircraft is used for all 20 weeks of the IERW common-core course. If the UH-1 track is not included in the discriminant classification procedure, the following correct classifications are realized: AH-1 track 72.0% correct; OH-58 track 79.4% correct; and UH-60 track 82.3% correct.

The UH-1 aircraft will be replaced (probably by the time this is published) by the TH-67 (a variant of the Bell 206) as the IERW common-core training aircraft. The multi-track classification procedure could be repeated with predictions made to all tracks from the new training helicopter (NTH). In summary, Intano and Howse wrote, "The Multi-Track Test Battery and Classification Functions alone or in combination with performance in primary training can adequately assign students to helicopter training tracks. The final validation classification functions are very similar to the original research functions derived from highly experienced Army aviators." (ref. 18, p. vi)

The selection and classification research summarized above shows that trainee success rates and, therefore, training effectiveness and efficiency, can be increased by screening applicants before training and by matching trainee abilities with aircraft and mission training requirements. In a cooperative effort among the services, selection and classification research will continue, with the goal of ever-increasing training effectiveness and efficiency.

THE STAIRWAY TO COMBAT READINESS: A MILITARY TRAINING APPROACH

Dohme and Gainer suggested the idea that the military training system may be productively viewed as a life-cycle management system (ref. 19). The military aviator's career

begins with his selection for initial entry training and ends with his retirement from the service, typically after 20 years of aviation assignments. During that life cycle, and as the aviator gains in rank and experience, it is typical that he be given more and more responsibility, for example, a transition to more complex aircraft and assignment to more demanding missions and their related duties. At each stage of the aviator's career, there is, at least theoretically, a training strategy or method that is best for sustaining combat readiness most efficiently at the lowest commensurate cost. The goal of aviation human factors researchers is to support the aviation commanders by developing training techniques that help them meet their requirements for efficient life-cycle utilization. Thus, the aviator life-cycle idea serves as a paradigm to drive and guide research in support of greater training efficiency and effectiveness.

Gainer, in an unpublished manuscript, calls this life-cycle training paradigm the "stairway to combat readiness." The application of the stairway to Army aviation training requirements is graphically portrayed in figure 3. Researchers at ARIARDA have found the stairway paradigm to be useful, both as a heuristic device for guiding research development and as a cogent means of communicating the training-requirements/research-capabilities interface to military managers and decision makers. In figure 3, the horizontal dimension portrays increasing training equipment complexity, and the vertical dimension portrays task complexity. As the trainee progresses up the stairway, the training tasks increase in complexity along several dimensions: (1) increased aviator task loading; (2) increased consequences of task failure; (3) increased complexity of aircraft/mission equipment; and (4) increased interdependency on other military personnel.

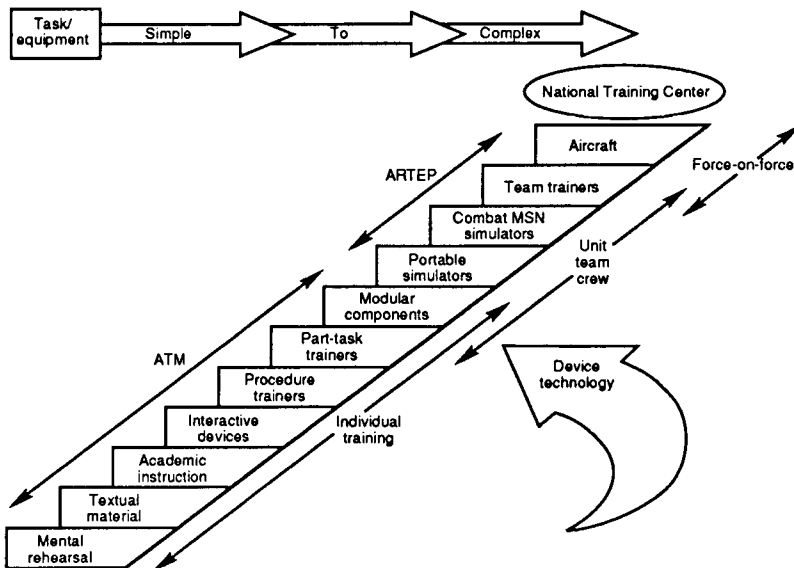


Figure 3. Stairway to Combat Readiness: A total aviation training system.

Research is under way at ARIARDA to address the training requirements generated by these increasing demands on aviator knowledge, skills, and abilities. The following four examples demonstrate the alignment of research applications with aviator life-cycle training requirements.

1. A technique has been developed to address aviator task loading called Task Analysis/Workload (TAWL) (ref. 20). The TAWL technique was developed for implementation on a PC computer in the TAWL Operator Simulation System (TOSS) (ref. 20). The TAWL/TOSS task-loading assessment model has been used to evaluate workload on several existing Army missions (refs. 21, 22).

2. Rotary-wing aviation accidents have been analyzed (e.g., by Zeller et al., ref. 23) leading to the formulation of a more effective model for accident prevention (ref. 24). Accident analysis led to the recognition that failure of *aircrew coordination* is an important causal element in aviation accidents. This line of research recognized the consequences of errors in aircrew coordination and guided the development of the aircrew coordination training package described in example 4 below.

3. ARIARDA has recently developed a facility called the Simulation Training Research Advanced Test-Bed for Aviation (STRATA); its purpose is to support research into the evaluation of mission-training efficacy as a function of simulator complexity. STRATA, which is currently configured as an AH-64 Apache, is a modular, reconfigurable simulator. Its capability of varying the levels of simulator fidelity can be used to determine the most cost-effective levels of fidelity and simulator complexity for supporting a given training requirement. STRATA can also simulate a wide variety of battlefield conditions in order to evaluate training concepts, for example, (1) how to effectively train a particular tactic or to evaluate the effectiveness of a particular aircraft modification, or (2) how to simulate the ballistics characteristics of an experimental weapon system. STRATA has an extensive recording capability so that both human performance measures and aircraft measures can be recorded, replayed, stored, and analyzed. These capabilities support the use of the device for evaluating training or aircraft/weapons systems capabilities or both.

Currently, the STRATA facility uses a high-fidelity, fiber-optic helmet-mounted display (FOHMD) with high-level-of-detail stereoscopic insets for the pilot's visual display and a rear projection wraparound display for the copilot-gunner. In recent research, the simulator has been used to evaluate the effect of visual-scene content and display configuration on nap-of-the-Earth (NOE) flight (ref. 25). In this exploratory experiment, three levels of tree density were used, three levels of texture detail, and three configurations of the FOHMD; 12 Army aviators, experienced in NOE flight, served as research subjects.

Results of the Hamilton and Wightman study (ref. 25) indicated that an aviator's ability to maintain an airspeed of 40 knots at less than 25 ft above ground level (AGL) was affected by the visual-scene content. The presence of trees (vs no trees) in the visual data base did produce better control of altitude, but the greater tree density was not significantly better than the lower density scene. The level of texture detail did not affect the

aviators' ability to maintain airspeed, but more detailed ground surface texture did result in a small (but significant) increase in the control of altitude. The three display conditions — eye-tracked area of interest (the high-detail foveal inset), fixed forward area of interest, and no high-detail area of interest — did not significantly affect NOE flight performance. This kind of psychophysical research on basic simulator parameters is needed to identify the tasks that can be effectively and efficiently trained in existing simulators and, more important, to affect the design of future rotary-wing simulators.

4. The requirement for aviator recurrency or enhancement training recognizes the need for aviators to work effectively with fellow crew members and with other military units (e.g., scout/attack teams, coordinated attack missions with USAF A-10 "Warthog" aircraft, or in artillery fire adjustment). The ARIARDA research program of aircrew coordination training is outlined later in this chapter. An exportable training package was developed, validated, and endorsed for Army-wide fielding by the Army Chief of Staff in FY93. Ongoing research is applying these crew-coordination training ideas to additional Training and Doctrine Command (TRADOC) training challenges. They include (1) M1A1 and Bradley Fighting Vehicle crew training; (2) Stinger Bradley Fighting Vehicle crew training; and (3) distributed, asynchronous training for battalion staff officers.

The stairway-to-readiness approach will continue to serve as a framework for an overall training system designed to bring Army training requirements into accord with training research efforts. The stairway idea has proved effective in conveying to Army leaders the complexities of aviation training requirements and the role that research can play in improving the overall quality of training.

FUNCTIONAL EVALUATION OF TRAINING

In FY77, the Army introduced a revamped IERW training curriculum at the U.S. Army Aviation Center (USAAVNC) at Fort Rucker, Alabama. The new curriculum was called the "175/40" program because it was composed of 175 aircraft training hours and 40 simulator hours. It replaced the previous "180/20" curriculum. There was a USAAVNC requirement to evaluate the new curriculum to see whether the cut in aircraft hours, replaced by additional hours of simulation, would have an effect on the quality of the IERW graduates.

An empirical evaluation of the 175/40 program was conducted in which the performances of the control group (180/20 graduates) and the 175/40 experimental group on 30 mission-oriented tasks were compared (ref. 26). The IERW graduates were followed to the field where their flight training records, at Fort Rucker and also field data accumulated in 6- to 32-week periods after their first unit assignments, were analyzed. The 30 mission-oriented tasks (e.g., plan night mission, perform NOE flight, select/provide vectors to holding area) were evaluated by operational unit instructor pilots and unit supervisors for both groups. One important finding was that the 175/40 graduates were rated as adequate on 27 of the 30 tasks, whereas the 180/20 graduates were rated as adequate on only 13 of the 30 tasks. The overall conclusion reached was that in a carefully designed training program aircraft hours can be replaced with simulator hours and still show improved training efficacy (although the training hour trade-off will not necessarily save one hour of aircraft time for each hour of simulator time).

In summary, program evaluation research in rotary-wing training appears to have merit if a mechanism is provided to feed back the research findings to curriculum developers. Given the numbers of people and dollars invested in military flight training, even modest improvements in training efficiency could pay large dividends in the form of increased combat readiness and reduced training costs.

DECAY AND RECOVERY OF PILOTING SKILLS

The literature on piloting skill retention suggests that procedural flight skills decay in a matter of weeks with no practice whereas psychomotor aircraft control skills are retained for months or even years without practice (refs. 27, 28). The literature also suggests that the amount of proficiency loss varies directly with the time since last flight and inversely with the level of experience of the aviator (refs. 29, 30). There is little specific information in the literature concerning rotary-wing skill decay and recovery rates. ARIARDA was afforded the opportunity to study the decay of rotary-wing piloting skills, as well as reacquisition rates, in research performed on the Individual Ready Reserve (IRR) aviator program.

IRR aviators are those who are members of the U.S. Army Reserve but who are not affiliated with an Active Reserve unit. IRR soldiers are controlled by a career manager who assigns training to the individual based on a flexible training program designed to maintain the "soldier skills" of each individual. In FY79, the Deputy Chief of Staff for Operations (DCSOPS) tasked ARIARDA to evaluate the IRR program to estimate rotary-wing skill decay rates in nonflying IRR aviators in order to determine the amount of retraining necessary for requalification and then to develop a cost-effective retraining program.

Wick et al. developed an academic self-study program to minimize the cost of academic retraining (ref. 31). In fact, as the research program progressed, IRR aviators were sent a self-study package they could use at home to facilitate learning of the academic information before their arrival at Fort Rucker for flight retraining.

Forty-seven IRR aviators, all of whom were UH-1 pilots, served as research subjects during the first year of the program (ref. 31). The subjects varied greatly in rotary-wing experience and in time-since-last-flight. Total flight hours varied from 235 to 4,300 with a median of 1,260. Years since last flown (active duty Army) varied from 1 to 19 with a median of 7.5.

Each subject was first given a proficiency flight evaluation using the standards published in the UH-1 Aircrew Training Manual (ATM) as criteria. None of the 47 was sufficiently skilled to pass the initial evaluative check-ride. There was great variability among the aviators and across tasks in flight proficiency levels. Training was conducted to ATM standards, and the average IRR pilot required 16.8 hours of retraining to pass the check-ride. The range was 10.5 to 25.5 hours.

One goal of the research program was to develop a practical analytical tool for predicting the amount of retraining required to requalify an IRR aviator for active duty. A multiple regression equation was developed that predicts the amount of retraining required to qualify an aviator once experience level (total flight hours) and currency (time since last active duty flight) are known (ref. 31). The equation is:

$$Y = 14.68 + 0.48X_a - 0.0015X_b$$

where

Y is the estimated number of training hours required

X_a is the number of years since last duty flight

X_b is the accumulated military rotary-wing flight hours

The multiple regression analysis yielded an R (coefficient of multiple correlation) of 0.57. This R value is statistically significant and large enough to be a practically useful predictor. Wick et al. showed that in the practical application of this equation, approximately 1 hour of flight time is required for every 2 years since the last duty flight (ref. 31).

The IRR flight requalification program requires individual pacing of instruction in order to be cost-effective. The academic training was found to be effective when self-paced. Some subjects completed a great deal of home-study before arriving at Fort Rucker and others completed none. The amount of home-study completed was not closely related to aviator motivation. Some highly motivated individuals either did not receive the home-study materials or were unable to rearrange their busy lives to allow for home-study.

A predictive equation was developed to estimate the amount of academic training that would be required to academically prepare the aviators (ref. 31). The equation is

$$Y = 5.62 - 0.66X$$

where

Y is the classroom days required to complete the academics

X is the home-study units (of 14) completed

Several conclusions have been drawn from the IRR program regarding rotary-wing flight skill decay and recovery. First, the basic psychomotor flight skills are relatively robust, requiring only modest retraining following relatively long periods of not flying. Second, specific procedural skills are lost when not practiced, but can be recovered in less training time than was originally required in learning them. Third, practical predictive equations can be developed to enable the training manager to accurately estimate the training time and cost necessary to requalify an individual whose flight currency

has lapsed. Finally, these findings imply that if time permits it may be more cost-effective to requalify certain military aviators as needed in wartime than to maintain currency of the entire aviator population.

FLIGHT SIMULATION AS A TRAINING EFFICIENCY MULTIPLIER

The military services pioneered the use of simulation to increase training efficiency. Since the development of Ed Link's "Blue Canoe" fixed-wing instrument trainer just before World War II, military aviation has made increasing use of flight simulation to supplement or replace actual flight hours. Yet the question may be asked, "How effective is simulation in bolstering the aviation training mission?" Surprisingly little research has been done to functionally analyze the contribution of simulator training to the overall flight training mission.

In a review of military simulator training effectiveness, Hayes et al. performed a meta-analysis of the literature (ref. 32). Their review was limited to experiments that met two criteria: (1) those in which training was conducted in a flight simulator and (2) those in which training effectiveness was measured in terms of transfer of training (TOT) from the simulator to the operational aircraft. Twenty-six experiments were identified that met these criteria (from a review of 247 journal articles and technical reports). The results of the meta-analysis were subdivided into two groups based on the training vehicle: jet aircraft or helicopter. In the rotary-wing category, they found only 7 studies, of the 26 that met review criteria.

The conclusions drawn from the meta-analysis were that simulator-based training consistently produced improved training for jet trainees but not for helicopter trainees. Specifically, "... findings from similar (to jet aircraft) helicopter experiments were less consistent and only slightly favored simulator training combined with aircraft training over aircraft training alone" (ref. 32, p. 150). Regarding simulator motion cueing, they concluded that simulator motion cueing did not significantly aid jet training, and there were insufficient data points to assess the effects of simulator motion for helicopter training.

From this meta-analysis of the rotary-wing simulator effectiveness literature, the most obvious conclusion is that more work is needed. Specifically, what is needed is research using empirical criteria for pilot evaluation, employing the same criteria in the simulator and the aircraft, using operational aviators (or trainees) as research subjects, measuring TOT, and presenting sufficient data to support future meta-analyses. Meeting these criteria makes the research effort expensive and time-consuming, but the alternative is what we have now — no clear guidance regarding the most effective and efficient design for rotary-wing training simulators.

Simulator Evaluation Research

Transfer of training (TOT) is commonly viewed in the simulation community as being the best available measure of simulator-based training effectiveness. Given that the final

criterion of flight training is a pilot's effectiveness in accomplishing a mission under demanding (high task-loading) conditions, then a measure of TOT to mission flight conditions is highly appropriate as a measure of training efficacy. In Chapter 4, Westra and Lintern provide a thorough review of TOT methods and of the evaluation of cost effectiveness in training. In this chapter, TOT and related techniques are viewed as tools for the evaluation of existing devices and for the development of better flight simulators and other training devices.

Backward transfer is a useful technique for evaluating existing flight simulators. In backward transfer, performance in the aircraft serves as the predictor, and performance in the simulator is the criterion measure. Backward transfer was used by Kaempf and Blackwell in an evaluation of the AH-1 Cobra Flight and Weapons simulator (AH-1FWS) (ref. 33). The authors reasoned that an individual who has demonstrated the capability of performing emergency touchdown maneuvers (ETMs) to published standards in the aircraft should also be able to perform those same maneuvers to the same standards in the simulator.

The ETMs evaluated were standard autorotation, low-level autorotation, low-level high-speed autorotation, right antitorque failure (stuck pedal), and dual hydraulics failure. Twenty AH-1 pilots in the field with varying experience levels served as subjects, and training was provided until each aviator was able to perform the ETMs within published standards. Half of the subjects were trained to standards in the aircraft (the experimental group) and half were trained to the standards in the AH-1FWS (the control group).

Aviators trained in the AH-1FWS were evaluated by means of a check-ride in the aircraft, and aircraft-trained aviators were evaluated in the simulator. This procedure allowed the calculation of both forward and backward TOT. The forward transfer results indicated that on only two of the five study maneuvers, standard autorotation and right antitorque failure, was there a moderate transfer of training to the aircraft (by the simulator-trained subjects). Backward TOT results demonstrated that none of the experimental group aviators (trained in the aircraft) performed the maneuvers successfully on their first check-ride in the simulator. In fact, considerable simulator training was required before these aviators could meet training standards in the AH-1FWS.

That so little backward transfer was observed indicates that there are substantial differences in the flight characteristics of the aircraft and the simulator. The authors point out, however, that "The lack of a high degree of backward transfer does not necessarily mean that the simulator has no training value" (ref. 33, p. 6). Nonetheless, the results do demonstrate that at least one existing Army training simulator is not a good analog of the aircraft it simulates.

Backward-transfer studies are useful tools for evaluating the training effectiveness of existing simulators. With repeated backward-transfer experiments, a simulator could be iteratively "tweaked" until it demonstrated improved backward TOT. This method has been proposed to USAAVNC, but has not been implemented to date on existing devices.

The more conventional measure of simulator training effectiveness is, of course, forward TOT. The research idea is simple: pretraining in the simulator should aid follow-on aircraft training as manifested in either reductions in the training time required or in the number of maneuver iterations required to meet standards in the aircraft. Dohme used this method to evaluate an experimental low-cost visual simulator called the UH-1 Training Research Simulator (UH-1TRS) (ref. 34). The UH-1TRS was developed to determine if ab initio students could be effectively and efficiently trained in primary rotary-wing flight maneuvers, particularly hovering maneuvers, in a simple, low-cost trainer. Seven experiments have been completed in which the UH-1TRS was used to address four research questions:

1. Does pretraining in the low-cost simulator transfer to the aircraft?
2. Can simulator training substitute for aircraft training in the IERW course?
3. Does simulator motion enhance hover training?
4. Can the simulator training be automated, that is, can basic maneuvers such as hovering be trained without an instructor?

The UH-1TRS was evaluated using TOT (transfer of training) as the primary research tool, and ab initio flight students served as the research subjects. The TOT experiments were embedded in the IERW course structure, using randomly selected Army trainees as research subjects and assigning them to training in the UH-1TRS before flight-line training. Training was conducted to criterion: three successive iterations of the training maneuver that meet the published standard in the Flight Training Guide (FTG). A transfer effectiveness ratio (TER) was calculated for each maneuver, using the following formula (adapted from Williges; ref. 35):

$$\text{TER} = \frac{C_I - E_I}{E_{I(\text{sim})}}$$

where C_I is the number of control group iterations, E_I is the number of experimental group iterations, and $E_{I(\text{sim})}$ is the number of experimental group iterations in the simulator.

Thus, the TER is a ratio of the savings in aircraft maneuver iterations (resulting from the simulator pretraining of the experimental group trainees) to the "cost" of that savings, that is, the number of iterations required for the experimental group trainees to reach criterion performance in the simulator. A simulator that is the equal of the aircraft as a training device (with the aircraft serving as the criterion measure) would evidence a TER of 1.0. Observed TER values can exceed 1.0 when the simulator is a more effective trainer than the aircraft, but TER values substantially less than 1.0 are most common in TOT experiments. Although the calculated TER values may be considerably less than 1.0, the simulator can nonetheless be an effective and efficient trainer, a result of the low

costs and risks associated with flight simulation. Helicopter training operations incur direct aircraft operating costs and myriad ancillary costs such as operating stage fields, operating communication and navigation facilities, maintaining a crash rescue service, and maintaining an aviation weather service. Simulation avoids these direct and ancillary costs and avoids the inefficiencies caused by weather-related training flight cancellations. In addition, simulation increases training efficiency by eliminating the need to join heavy traffic in order to leave the heliport and fly to a stage field where primary maneuvers such as hovering flight and traffic pattern flight can be trained. Simulators also increase training effectiveness by using initial condition (IC) sets that allow training to begin from a location other than the parking ramp at the heliport. Only in a simulator can the SP practice, say, 20 approaches without flying a single departure or traffic pattern! These advantages to simulator-based training serve as training effectiveness multipliers and render a device with only moderate TER values an efficient trainer.

There were eight primary phase maneuvers: takeoff to hover; hover taxi; hovering turns; hovering autorotation; normal takeoff; traffic pattern; normal approach; and land from hover.

The trainers were all instructor pilots (IPs) qualified to teach Primary Phase. In each case, students were trained for 1 hour/day in the UH-1TRS.

There were specific variations among the four TOT research studies. In overview, the first effort was a process evaluation of the simulator to see whether it provided any TOT to the UH-1 aircraft, using student pilots (SPs) who had already completed Primary Phase training (Experiment 1); the second and third were conventional TOT evaluations with neophyte trainees (Experiments 2 and 3); and the fourth was a "substitution" study in which 7 hours of UH-1 aircraft time was replaced by 9 hours in the simulator (Experiment 4).

The research plan proposed to substitute 9 hours of simulator training for 9 hours of aircraft training (in a 50-hour Primary Phase curriculum). However, weather conditions on the flight line limited the control group trainees to just over 7 hours of training during the time period allotted to the experiment.

Since the four experiments differ in several details, their results are presented separately below.

Experiment 1

The first experiment, conducted in June 1988, was a process evaluation designed to evaluate the potential of the newly constructed UH-1TRS. The purpose of the experiment was to evaluate the simulator by training students, who had already demonstrated their proficiency on Primary Phase maneuvers in the TH-55 training helicopter, on the same basic maneuvers in the UH-1TRS. Trainees were randomly selected to serve as research subjects immediately after completing Primary Phase IERW. The 10 randomly selected SPs received 2 weeks training in the eight maneuvers mentioned above (takeoff to hover;

hover taxi; hovering turns; hovering autorotations; normal takeoff; traffic pattern; normal approach; and land from hover) before they went to the flight line to begin flying the UH-1 helicopter. A control group (having no training interposed between the Primary Phase and the UH-1 Transition Phase) was selectively matched to the experimental SPs based on Primary Phase flight grades, Flight Aptitude Selection Test (FAST) scores, rank, and age. The matched pairs flew as "stick buddies" in the UH-1 with the same IP to further reduce variance in the experimental design. To ensure a fair and unbiased evaluation, the IPs did not know which SPs in the class had been pre-trained in the simulator.

Since this was the first evaluation of the low-cost simulator, and since experimental and control group trainees had met the same training requirements in Primary Phase, there were several possible research outcomes: (1) the UH-1TRS could demonstrate positive TOT; (2) the UH-1TRS could demonstrate no TOT; and (3) the UH-1TRS could demonstrate negative TOT.

Actual results suggest that the UH-1TRS as it was configured for Experiment 1 with very low-cost image generators (IGs), IRIS 2400Ts, and a relatively primitive aerodynamic model, that is, the NASA "Uncle" model (see ref. 36) provided all three of the possible outcomes depending on the maneuver analyzed (see fig. 4). The TER, averaged across all maneuvers, showed an overall positive transfer (TER = 0.22).

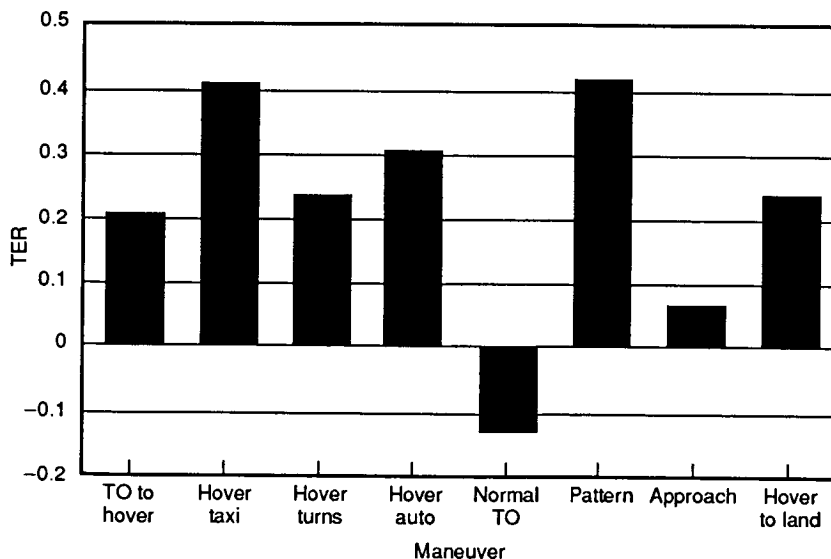


Figure 4. Transfer effectiveness ratio (TER) values for Experiment 1.

Results of Experiment 1 showed moderate evidence of TOT. Figure 4 presents the TER for each maneuver. On six of the eight maneuvers, modest positive TERs were demonstrated; on one the TER was zero; and on one (takeoff) the TER was negative. The TERs can be presented in an alternative format to provide a practical index of the amount of training transfer expected in an applied training scenario. Figure 5 presents the reciprocals of the TERs (termed "iterations transfer ratios" or ITRs) which reveal the number of simulator iterations required to save one aircraft iteration on the flight line. In other words, the ITR represents the "simulator cost" of saving one aircraft maneuver iteration.



	 ITR 	
	UH - 1TRS	Aircraft
TO to hover	___ 4.76	___ 1
Hover taxi	___ 2.45	___ 1
Hovering turns	___ 4.17	___ 1
Hover autorotation	___ 3.23	___ 1
Normal takeoff		___ 1
Pattern	___ 2.38	___ 1
Approach	___ 14.3	___ 1
Hover to landing	___ 4.17	___ 1

Figure 5. Iterations transfer ratio (ITR) values for Experiment 1.

Experiment 2

The modest TOT observed in Experiment 1 demonstrated that it would be worthwhile to perform a full-fledged TOT experiment. For Experiment 2, several improvements were made to the simulator:

1. The image generators were upgraded to BBN 120TX/Ts, which improved out-of-window imagery in at least four important ways: the frame update rate went from 17 Hz to 30 Hz; the displayed polygon count went from 300 to 1000; the capability of surface texturing was added; and, a realistic terrain model (of Fort Knox, Kentucky) was used in place of the primitive flat Earth model.

2. The aerodynamic simulation was improved by developing a ground-effect model and improving the handling characteristics of the UH-1TRS by having test pilots

iteratively fly the device and the UH-1H helicopter and then "tweak" the aerodynamic equations in response to their suggestions.

In Experiment 2, conducted from February-April 1989, 10 Army flight students were randomly sampled from an IERW class with the stipulation that none of them had prior flight experience. Their training schedule was altered to provide preflight academic training 2 weeks early in order to create a 2-week period for simulator training. Test subjects were trained to criterion on the previously described eight target maneuvers; the training was done by IPs qualified to teach Primary Phase students. An average of 8.7 hours of training per student was required in order for them to meet criterion performance on all maneuvers (contrasted with 6.3 hours average for the SPs in Experiment 1 who had prior training).

Figure 6 shows the TERs for Experiment 2, and figure 7 shows the same data in the form of iterations transfer ratios. These data show a moderate improvement in TOT from that of Experiment 1. For six of the eight target maneuvers, there was a positive TOT, with one essentially zero, and one negative. The overall average TER was 0.36.

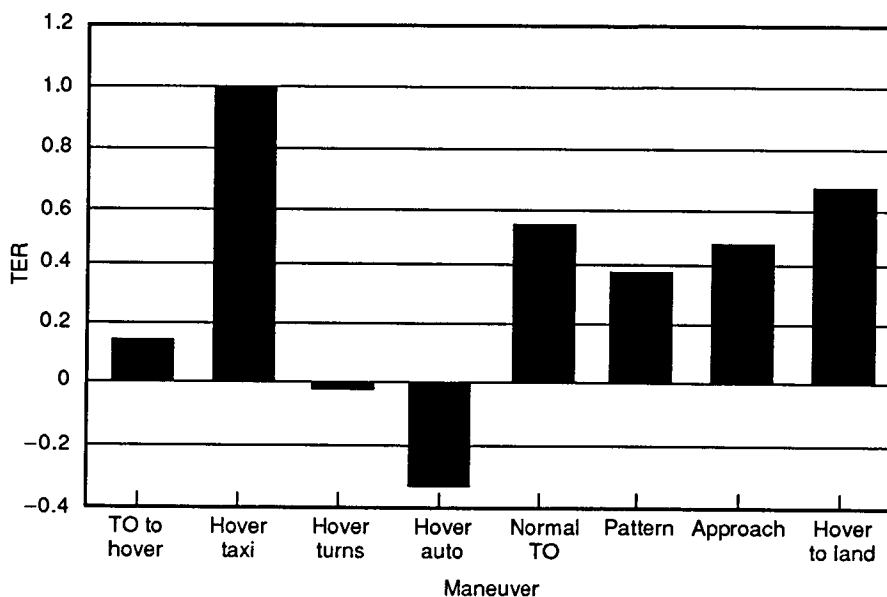



Figure 6. Transfer effectiveness ratio (TER) for Experiment 2.



	UH - 1TRS	Aircraft
TO to hover	6.67	1
Hover taxi	1.0	1
Hovering turns		1
Hover autorotation		1
Normal takeoff	1.85	1
Pattern	2.63	1
Approach	2.13	1
Hover to landing	1.49	1

Figure 7. Iterations transfer ratio (ITR) values for Experiment 2.

The overall higher TER in Experiment 2 might be a function of the improvements to the simulator configuration or it could be the result of using neophytes as subjects for whom the degree of improvement in flight skills is expected to be extremely large during the first few weeks of training.

Experiment 3

Another TOT experiment, Experiment 3, using ab initio trainees as research subjects was conducted from September-November 1989. Improvements were again made to the UH-1TRS before the research was conducted. The BBN 120TX/T image generators were temporarily replaced with Evans and Sutherland ESIG 500H IGs. This improved the image quality by speeding the frame update rate from 30 to 50 Hz, by improving the level of detail (LOD) management and texturing capabilities, and by providing additional features such as weather effects. A custom data base was developed that modeled a portion of the Fort Rucker Area of Operations (AO). The experimental procedure followed was exactly the same as that for Experiment 2.

The TER values for Experiment 3 are presented in figure 8, and the derived iterations transfer ratios are presented in figure 9. In this experiment, there was a positive TER for all eight maneuvers. The iterations transfer ratios varied from 1.37:1 for hover taxi to 4.0:1 for takeoff to hover. The average of these iterations transfer ratios was 2.32:1, which suggests that under these conditions, two and one-third maneuvers in the simulator will save one maneuver on the flight line. Given the low hourly operating cost of the UH-1TRS (about \$50/hr; the UH-1H costs about \$700/hr) plus the increased training efficiency associated with simulation, these results suggest that the UH-1TRS is an effective trainer. The overall average TER for Experiment 3 was 0.45.

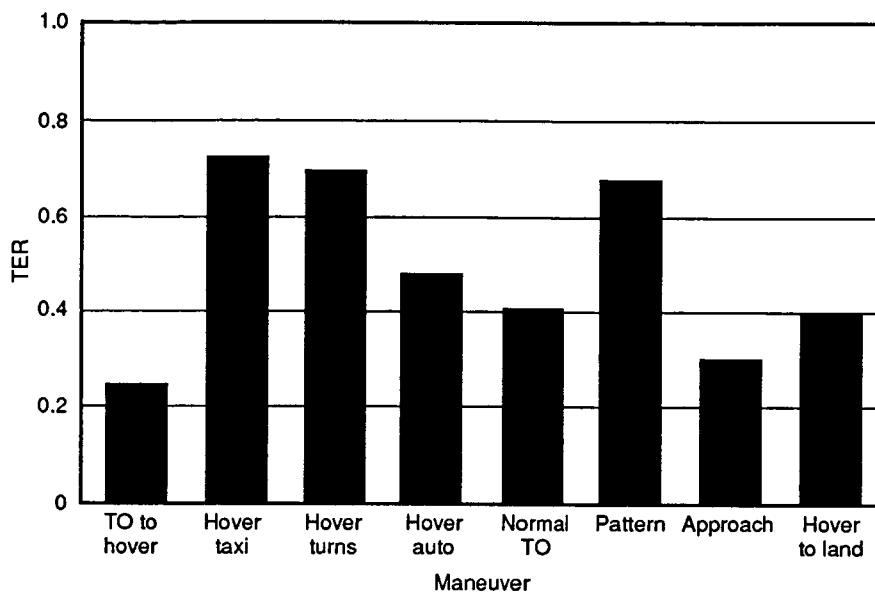


Figure 8. Transfer effectiveness ratio (TER) values for Experiment 3.



		ITR	
	UH - 1TRS		Aircraft
TO to hover	4.00		1
Hover taxi	1.37		1
Hovering turns	1.43		1
Hover autorotation	2.08		1
Normal takeoff	2.34		1
Pattern	1.47		1
Approach	3.23		1
Hover to landing	2.50		1

Figure 9. Iterations transfer ratio (ITR) values for Experiment 3.

Experiment 4

Experiment 4 was called the substitution experiment. Prior research demonstrated that the UH-1TRS could produce a positive training benefit when introduced as an adjunct to an existing fixed-hour training course. However, an adjunct training schedule offers no cost savings over costs in the current IERW training course. The substitution study was conducted to evaluate the feasibility of replacing "blade hour" (aircraft) training with low-cost simulation. Since it was determined in Experiments 2 and 3 that the average trainee meets the criterion on all eight training maneuvers in about 9 flight hours, the substitution study replaced about 9 hours of blade time with 9 hours of UH-1TRS time. The configuration of the UH-1TRS for the substitution experiment was the same as that for Experiment 2.

The dependent measures of greatest interest in the substitution study were not TERs; they were instead measures of the overall progress of students in training. Specifically, the focus was on whether the progress of the experimental group trainees would equal that of the aircraft control group trainees through the Primary Phase, as well as in training grades. The simplest measure of this progress is whether any experimental students were set back or eliminated from training in Primary Phase. As it turned out, there were no setbacks or eliminations from either the experimental or control group. Flight training grades at the end of the Primary Phase were compared, and the control group had slightly higher grades than the experimental group, but the difference was not statistically significant.

The TERs for Experiment 4 are presented in figure 10. A positive TOT was achieved on six of the eight target maneuvers; there was essentially no transfer on normal takeoff, and a slightly negative transfer on the hover taxi maneuver. The associated iterations transfer ratios are presented in figure 11. The overall average TER for Experiment 4 was 0.23. In general, the substitution experiment is considered to have had a successful outcome because of the following:

1. No experimental group SPs were set back or eliminated from Primary Phase training.
2. There was no significant difference in Primary Phase grades between the experimental and control SPs.
3. There was a net savings in training costs in Primary Phase (about \$36,600 for 10 trainees).
4. A degree of positive TOT to the flight line was demonstrated.

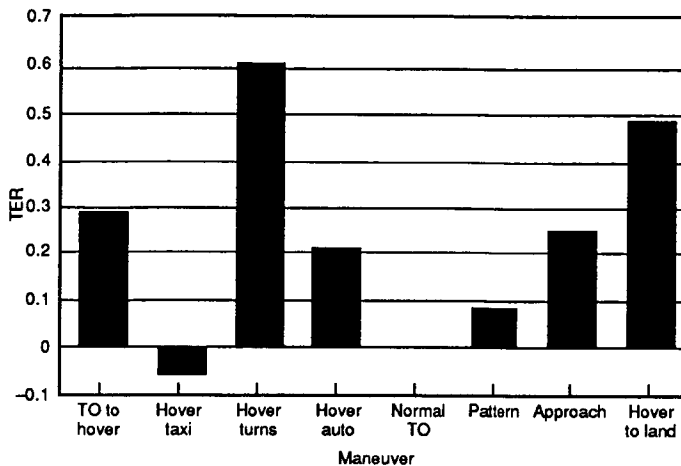


Figure 10. Transfer effectiveness ratio (TER) values for Experiment 4.



	 UH - 1TRS	 Aircraft
TO to hover	3.14	1
Hover taxi		1
Hovering turns	1.64	1
Hover autorotation	4.76	1
Normal takeoff		1
Pattern	11.10	1
Approach	4.17	1
Hover to landing	2.04	1

Figure 11. Iterations transfer ratio (ITR) for Experiment 4.

Experiments 1-4: Conclusions

The overall results across these experiments show that the UH-1TRS is capable of producing positive transfer of training to the UH-1 aircraft with Army flight students as research subjects. However, considerable variability is evidenced in TERs across studies. Some of this variability is probably attributable to changes in simulator configuration, some to differences in IP experience and skill levels, and some to individual differences in trainee abilities. Figure 12 shows the total TER values summarized across the four experiments, that is, averaged across 40 IERW trainees. Similarly, figure 13 summarizes the ITR values for the four experiments.

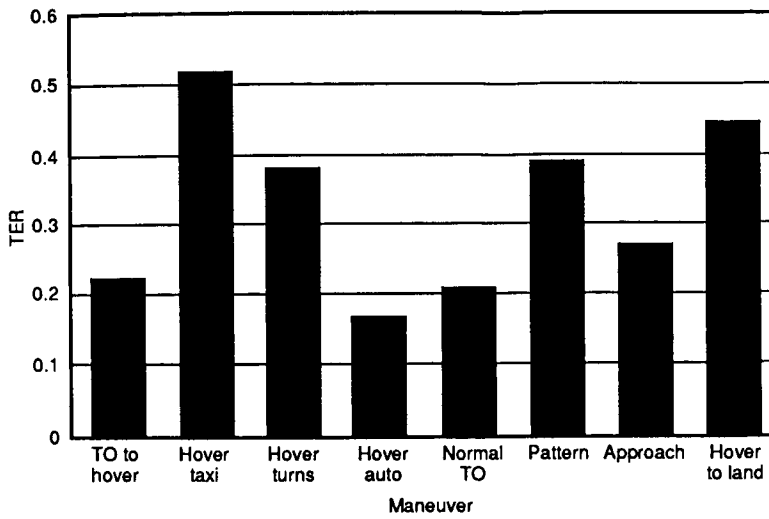


Figure 12. Summary of transfer effectiveness (TER) values for Experiments 1-4.



		ITR	
	UH - 1TRS		Aircraft
TO to hover	___ 4.4		___ 1
Hover taxi	___ 1.92		___ 1
Hovering turns	___ 2.60		___ 1
Hover autorotation	___ 5.95		___ 1
Normal takeoff	___ 4.88		___ 1
Pattern	___ 2.25		___ 1
Approach	___ 3.64		___ 1
Hover to landing	___ 2.22		___ 1

Figure 13. Summary of iterations transfer ratio (ITR) values.

In summary, the UH-1TRS demonstrates that low-cost simulation has considerable potential to train neophyte Army flight students in the basic skills of rotary-wing flight. The TOT results demonstrate that the UH-1TRS is a practical training device and that it could reduce Primary Phase training costs if simulator time were substituted for helicopter flight time.

The UH-1TRS has been improved in several ways since the completion of the four experiments summarized above. The Uncle aerodynamic model from Ames Research Center has been replaced with the ARMCOP model, also developed at Ames. The ARMCOP model was improved by enhancing its low-speed and in-ground-effect (IGE) characteristics. A UH-1H aircraft was instrumented with accelerometers (three-axis), and test flights were conducted to evaluate the aircraft characteristics, especially in the region of effective translational lift (ETL). These characteristics were incorporated into the UH-1TRS aerodynamic model. The computer complex was upgraded to solve a problem with the unreliability of the host computer. Most importantly, the device was used as a vehicle for the development of an automated training system that could be used to train neophytes to hover without requiring the participation of an IP.

THE AUTOMATED HOVER TRAINER

One of the critical flight skills that must be learned by ab initio trainees in the IERW training program is hovering. Hovering maneuvers such as stationary hover, hover taxi, hovering turns, and takeoff to and land from a hover must be mastered before the trainee can solo the aircraft and go on to master advanced skills such as instrument flight, emergency procedures, and combat skills. Learning to hover has been traditionally trained using the "monkey see, monkey do" method in which an instructor pilot demonstrates hovering flight; after the demonstration, the trainee practices the maneuver while the IP guards the flight controls for safety and provides guidance to the trainee. In the IERW curriculum, the trainee must learn coordinated hovering skills before the 20th flight training hour in order to be cleared for solo flight and to avoid being eliminated from the training curriculum.

Successful hovering flight requires the coordinated use of the helicopter flight controls in order to overcome the interactions built into the aircraft. For example, when power is added by raising the collective-pitch lever in order to climb to a higher hover height, there must be a concomitant increase in the pitch of the anti-torque rotor (tail rotor), which is accomplished by adding left pedal. A UH-1 Huey helicopter, which is currently the Army's primary flight trainer, hovers with the nose 5° high (because of a 5° forward tilt to the main-rotor mast) and slightly "left skid low" in order to compensate for translating tendency, which is the effect of the anti-torque rotor acting as a propeller and trying to move the entire aircraft to the right. Any change in one helicopter control position requires a concomitant change in other controls to maintain the aerodynamic balance required for stable hovering flight. These control interactions and the rapid but small control movements required to maintain a constant position over the ground with varying wind conditions constitute a large part of the challenge that trainees must meet to learn hovering flight within the time allotted by the training syllabus.

The idea of a simulator-based automated hover trainer occurred to the author during his first attempts at hovering flight in 1977. In particular, the standard training method of giving the neophyte trainee only one control at a time is at variance with known human factors principles. For example, a literature review by Wightman and Lintern drew the conclusion that integrated manual control tasks should not be fractionated for training (ref. 37). However, the problem with hover training is that most ab initio trainees cannot handle all the aircraft controls at one time without compromising flight safety. Thus, the standard training method used by the Army is to first give the trainee control of only the pedals, next, only the cyclic, then only the collective. The problem with this approach comes when the trainee tries to integrate the separately learned control responses by taking responsibility for all controls simultaneously. The literature review by Wightman and Lintern suggests that the integration time for separately learned tasks is longer than the time required to learn the tasks simultaneously in an integrated approach (ref. 37).

So on the one hand, the human factors literature suggests that integrated psychomotor tasks such as operating flight controls should not be fractionated for training, but considerations of safety say that neophyte trainees should not be given all the controls simultaneously in hover training. The solution to this apparent quandary is to accomplish hover training in a simulator with built-in stability augmentation such that the neophyte can successfully operate all the controls in a hover from the first attempt. The stability augmentation should be variable, capable of providing substantial help to the neophyte and much less to the trainee who has nearly learned the hovering tasks. Ideally, the amount of stability augmentation help should be varied intelligently in response to the level of performance of the trainee, that is, should adaptively help the student by augmenting control stability only to the degree needed by the trainee to retain basic aircraft control.

This is the premise that served as a foundation for the development of the Automated Hover Trainer (AHT). A simulator-based trainer was envisioned that would continuously review trainee performance and adaptively augment control inputs such that the demand characteristics of the simulator would accommodate the trainee's ability to successfully hover.

These human factors considerations drove the engineering requirements for the development of the AHT. Aerospace and electrical engineers at the University of Alabama applied the Optimal Control Model to the design of an adaptive trainer providing inner loop stability augmentation (ref. 38). The mathematical model periodically compares trainee performance with expert performance norms based on a highly skilled pilot flying the same maneuver without augmentation. As the trainee's performance approaches the norm, the computer software switches to a lower level of augmentation until the student is flying the unaugmented helicopter aerodynamic model (ref. 39).

A series of experiments was undertaken to evaluate the training effectiveness of the AHT. Again, Army IERW trainees served as research subjects and the experiment was embedded in the IERW course. In the first experimental evaluations of the effectiveness of the AHT, a standardized evaluative check-ride in the simulator was administered

following automated training. In follow-on experiments, TOT from the AHT to the UH-1 aircraft was measured. The following two sections present the methods and the results of the AHT experiments.

QUASI-TRANSFER EXPERIMENTS

In 1989, a preliminary evaluation of the AHT was accomplished using what Roscoe and Williges termed a "quasi-transfer" method, that is, the transfer was evaluated by using the simulator itself as the criterion vehicle (ref. 35). Twenty-four warrant officer candidates awaiting flight training served as research subjects. Each was trained to FTG criteria on five hovering maneuvers: stationary hover, hover taxi, hovering turns, land from hover, and takeoff to hover. The defining criteria for these maneuvers follow.

1. *Stationary hover*: hover 3 feet behind the Maltese cross, in alignment with the runway, at skid height of 3-5 feet.
2. *Hover taxi*: taxi down the centerline of the runway at a skid height of 3-5 feet at a speed not to exceed that of a brisk walk.
3. *Hovering turn*: maintain the aircraft over a fixed point on the runway at a skid height of 3-5 feet; perform a 90° pedal (yawing) turn to the right; perform a 90° pedal turn to the left to return to the initial heading.
4. *Land from hover*: smoothly reduce collective pitch to land from a stationary hover, maintaining runway alignment and position over the ground.
5. *Takeoff to hover*: smoothly increase collective pitch to bring the aircraft to a 3-5-foot hover maintaining runway alignment and position over the ground.

The five hovering maneuvers were trained in the order in which they are listed above. In the hover training program, the simulator initiated stationary hover training by performing an "autotakeoff," that is, by automatically performing a normal takeoff to a 3-foot hover. The trainee was advised to follow through on the controls to experience a demonstration of a normal takeoff. When the simulator reached a skid height of 3-5 feet, the "autotakeoff" was terminated, and control authority was given to the trainee, who began learning the sensorimotor coordination required to perform a stationary hover. The autotakeoff feature was used to initiate training on the first four maneuvers.

The artificial intelligence (AI) logic that created the "autohelp" training function was described by Krishnakumar et al. (ref. 39). The autohelp function, created by application of the optimal control model (OCM) with an internal feedback loop, augmented the trainee's control inputs to damp out overcontrolling responses. All trainees began at autohelp level 6 (of 12 levels). The goal for the trainee was to quickly reduce the amount of autohelp provided from level 6 to level 0 (level 0 was the unaugmented UH-1 aero model) by matching his performance with the OCM "expert" model. Criterion

performance was defined as 2 successive minutes at autohelp level zero. It was common for trainees reaching level zero to return to level 1 and, occasionally, even level 2 before finally mastering the control movements required to maintain the model at level zero.

When the trainee had met the 2-minute criterion on stationary hover, hover taxi, hovering turn, and land from a hover, the AHT initialized on the ground and the trainee made the first unassisted attempt at takeoff to a hover. When the criterion was met for all five maneuvers, training was considered completed. This training took place in approximately 1-hour training sessions over four consecutive training days. On the fifth day, each trainee took a "check-ride" in the simulator.

Simulator check-rides were administered by an Army rated standardization instructor pilot (SIP) who was not privy to the training data for the research subjects. The SIP graded the subjects on a pass/fail basis. Subjects were graded as though they were being evaluated for authorization to perform solo flight, a check-ride which was, at that time, administered at approximately the 14-hour training level. These were highly conservative standards in that the subjects trained in the AHT had received only an average of 3.1 hours of training at that time. Total training time was limited by the schedule imposed on the research subjects by their Army assignments.

Two criteria were used to determine the effectiveness of the automated training:

1. Was the trainee able to progress through the automated training paradigm and meet the criterion during the 4-day training period?
2. Was the trainee able to achieve a passing score on the maneuver during the check-ride?

Figure 14 presents the data that answer these questions. Twenty one of the 24 trainees met the training criterion on all five hovering maneuvers; one did not successfully meet the criterion on stationary hover, hovering turn, or land from a hover, and two were unable to meet the criterion on takeoff to a hover (the most difficult maneuver to perform within standards). Only 23 of the experimental students were available to take the in-simulator check-ride. All 23 passed the check-ride on the stationary hover, hover taxi, and hovering turn maneuvers. Twenty two of the 23 passed the check-ride on the remaining maneuvers, that is, land from a hover and takeoff to a hover. Therefore, these quasi-transfer results are considered to have demonstrated the effectiveness of the AHT approach.

TRANSFER-OF-TRAINING EXPERIMENTS

The quasi-transfer research was viewed as a process evaluation that revealed the effectiveness of the AHT approach. However, the quasi-transfer results could not predict the effectiveness of the trainer in the trainee's subsequent performance in the aircraft. What was needed was a full-fledged TOT evaluation of the AHT to determine whether the

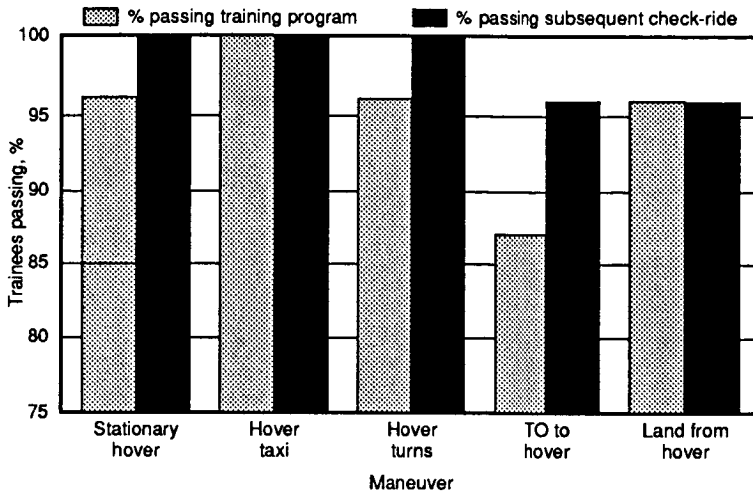


Figure 14. Trainees meeting criterion for maneuver training and trainees passing check-ride.

device had a practical application in reducing training costs and increasing training efficiency in the IERW course. Two such evaluative experiments were conducted using Army flight students in the IERW curriculum as research subjects and using TOT to the UH-1 aircraft on the flight line as the criterion for the performance of the trainer. Each experiment employed 10 SPs as research subjects. Since only 10 subjects could be trained in the simulator per day, the experiment was duplicated in order to increase the number of subjects and, thereby, to increase the statistical power of the results. Thus, the two experiments have been combined in this review.

Twenty officer trainees, drawn from their training classes at random, learned to hover in the AHT before beginning training in the UH-1 aircraft. Their progress in the IERW training program was evaluated to assess TOT to the UH-1 aircraft. A special evaluation slip was developed to measure trainee progress in hovering skills. On the evaluation slip, which was completed daily, the Primary Phase instructor pilot (IP) recorded the number of times each hovering maneuver was demonstrated, each trainee attempt at the maneuver, whether the IP touched the controls (either to "save" the aircraft or for training purposes), and whether the trainee completed the maneuver within Flight Training Guide (FTG) standards. The evaluation slip, which fitted on the IP's kneeboard, defined the four outcome categories for each trained maneuver:

1. Demo: IP demonstrates maneuver
2. Assist: SP attempts maneuver, IP takes over controls to assist
3. Attempt: SP completes maneuver without help, but does not meet standards
4. Standard: SP completes maneuver, meets standards

Each hover maneuver was scored in one of the above categories. Successful completion of training for each maneuver was operationally defined as three successive maneuver iterations in the Standard category.

TOT was assessed by comparing the hover training performance of the experimental group with that of their classmates in Primary Phase IERW. Each AHT-trained student was paired with a classmate who had no prior training and who thus served as a control. Before the selection of the experimental group, all members of the two classes that provided subjects for this research were administered an aviation experience questionnaire. All trainees who had prior flight training were eliminated from consideration, as either experimental or control subjects. Since each primary phase IERW instructor pilot trains student pilots in pairs, this pair-wise comparison of "stick buddies" served to reduce the variance caused by differences in IP training style, aircraft flight characteristics, time of day, or weather conditions during training.

The assumption was made that prior hover training in the simulator should reduce the number of maneuver iterations to criterion for a given maneuver when that same maneuver was performed in the aircraft. Specifically, the experimental group should meet the criterion of three successive maneuvers to standards in fewer iterations than their control group counterparts. This was the hypothesis tested in this experiment: the experimental trainees would require significantly fewer maneuver iterations than their control group counterparts to meet the training standard for hovering maneuvers.

In flight training, it is customary to quantify flight experience in terms of the total number of hours the individual has flown. We chose to count maneuver iterations rather than flight hours because the IERW curriculum includes other maneuvers, in addition to hovering flight, during the early training hours of the Primary Phase curriculum. Thus, without a special curriculum developed to train hovering flight before training in nonhovering maneuvers, it is not possible to know exactly how many training hours were required to meet the criterion on hovering maneuvers. It was, however, relatively straightforward for the IP to complete a scoring sheet each time a hovering maneuver was trained.

Maneuver standards were taken from the published IERW Flight Training Guide. The criterion for successful learning of each maneuver was three successive maneuver iterations within standards. The overall measure of trainee performance in training was the total number of maneuver iterations required to meet the criterion (including the three that defined the criterion).

The TOT experiment results are presented in figure 15. This figure compares iterations to criterion for the two groups by maneuver. In each case the experimental SPs met the criterion in fewer iterations than did the control group. This finding supports the research hypothesis.

A chi-square test of significance was performed to see if the better training performance of the experimental trainees exceeded chance variability at the 5% level of

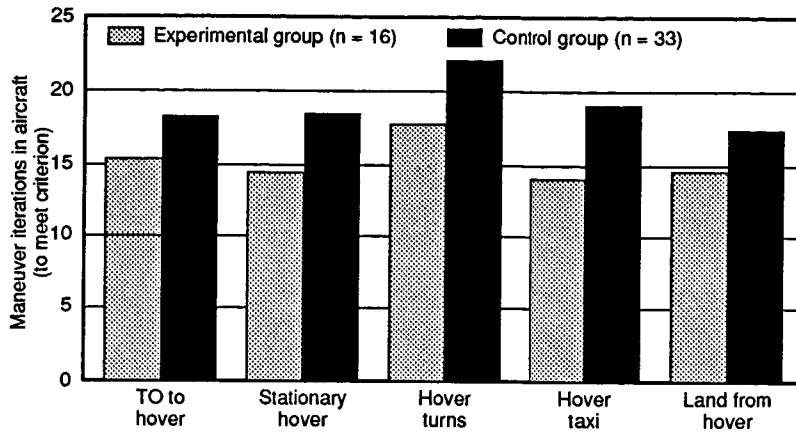


Figure 15. Mean maneuver iterations to standards for experimental and control groups.

confidence. The test results of the chi-square hypothesis are presented in table 1. This table presents the total number of maneuver iterations, by maneuver, observed for the two groups and the expected number of iterations under the chi-square model of no significant differences between the groups. The calculated chi-square values and associated probabilities show that the observed differences all met the criterion for statistical significance.

Table 1. Chi-square Test of Significance for Student Pilot Maneuver Iteration Data

	T/O to hover	Stationary hover	Hovering turn	Hover taxi	Landing from hover
Experimental group					
Observed ^a	245	228	281	226	234
Expected ^b	276.2	271.6	326.8	278.8	262.8
Control group					
Observed ^a	601	604	720	628	571
Expected ^b	569.8	560.4	674.2	575.2	542.4
χ^2 value	524	10.41	9.54	14.86	4.69
Significance (d.f = 1)	p < .05	p < .01	p < .01	p < .001	p < .05

^a Total number of observed iterations.

^b Number of iterations expected under the chi-square model of significant difference between groups.

Table 2 summarizes the results across the five training maneuvers. The experimental group trainees met the criterion with an average of 15.2 iterations per maneuver and a total of 75.9 iterations to meet the criteria for all five maneuvers. The control group required an average of 18.9 iterations per maneuver with a total of 94.7 iterations for all five maneuvers. This difference reflects a savings of 19.9% of the control group's maneuver iterations on the flight line.

Table 2. Transfer of Training: Automated Hover Trainer to Aircraft

AHT training time per student pilot to learn five hover maneuvers ^a prior to aircraft training	2.9 hr
Iterations required per student pilot to meet criterion in aircraft: five hover maneuvers ^a	
Control group (no AHT time)	94.7
Experimental group (prior AHT time)	75.9
Iterations saved by prior AHT time	18.8 (19.9%)

^a Stationary hover, hover taxi, hovering turn, land from hover, takeoff to hover.

The research summarized above demonstrates (using Army trainees as research subjects) that the AHT approach is feasible and that the UH-1TRS is a practical training device capable of producing positive TOT in the IERW curriculum. These evaluations were performed within the context of the existing IERW training curriculum. Since the IERW curriculum was not developed to optimize the training effect of simulator-based training, it is assumed that the degree of TOT observed is a conservative estimate of the potential for low-cost simulation. Specifically, the "lock-step" IERW flight curriculum has a fixed training agenda that introduces hover training only on the third flight training day. Hover training is then integrated with other training objectives such as flight from the heliport to the stage field, traffic pattern flight, radio procedures, cockpit procedures, and simulated emergency procedures.

It would be informative to develop a training curriculum specifically tailored to the use of simulation and automated training. Criterion-based hovering performance was achieved in about 3 hours in the AHT and in about 10-14 hours in the aircraft. Thus, it appears that automated simulator-based training is highly efficient. However, the ultimate efficiency of this training medium remains to be proved in an experimental curriculum developed to optimize the application of low-cost training technology to primary rotary-wing training.

The ongoing direction in this research effort is toward an amplification of the AHT approach producing a full-fledged intelligent flight trainer (IFT). The IFT, which is being developed by ARIARDA and Charles River Analytics, capitalizes on the success of the AHT by applying advanced AI concepts to ab initio rotary-wing training. The IFT will adapt intelligent tutoring systems (ITS) technology (ref. 40) to adaptive training

techniques to synthesize an adaptive automated trainer module that can be interfaced with a wide range of simulators. Its first application will be to an ab initio rotary-wing trainer, such as the UH-1TRS. An attempt will be made to automate training of the entire IERW Primary Phase curriculum.

AIRCREW COORDINATION TRAINING

In the 5-year period FY84-89, Army aviation accidents cost 147 lives and \$292,000,000. The overall fatality rate remains relatively low given the hazardous conditions under which many missions are conducted (e.g., actual combat, NOE flight, and flight using night-vision devices), and the number of hours flown by Army aviation. (Army rotary-wing aircraft fly about 1.4 million hours per year for a fatality rate of about 1 death per 50,000 rotary-wing flight hours.) Nevertheless, these data show that there is still considerable room for improvement in Army flight safety.

According to Leedom, human error is identified as a causal factor in 70%-80% of all aviation accidents (ref. 41). A follow-up analysis by Simon of rotary-wing accident data revealed that an element in the causal chain in many accidents is a failure of the aircrew to appropriately allocate the mission tasks and functions, that is, failure of aircrew coordination (ref. 42). A similar analysis by Orlady and Foushee of U.S. Air Force accidents led to much the same conclusion and to the development of training in what is commonly termed *cockpit resource management* (ref. 43).

The unique environment in which Army rotary-wing missions are conducted, for example, at NOE altitudes at night using night-vision devices, required a fresh approach to aircrew coordination training. The exigencies created by a cockpit emergency under these conditions are often less tolerant of crew coordination errors than those occurring at 30,000 ft. In 1989, ARIARDA began a cooperative research effort with the U.S. Army Aviation Center (USAAVNC) and Dynamics Research Corporation (DRC) to evaluate Army rotary-wing accidents, to develop a research-based approach to crew coordination training, and to develop a method for evaluating the success of the training.

This cooperative research approach to aircrew coordination training focused on the evaluation of training outcome as the area with the greatest need for additional work. Aviation accidents are rare events when viewed as an accident rate. And rare events are notoriously difficult to predict by using stochastic models. Prior research in crew coordination, for example, in the commercial aviation industry, used measures of attitude change to assess training effectiveness rather than the more desirable direct measures of aircrew performance such as cockpit behaviors, accident rates, and mission effectiveness. The approach developed by Grubb et al. identified three levels of aircrew effectiveness: attitude, crew behavior, and crew performance (ref. 44).

Attitude was measured by using the Army Aviation Crewmember Questionnaire, which was adapted and enhanced from the military version of the Cockpit Management Attitudes Questionnaire (CMAQ) (refs. 45, 46). However, the attitude measure was found

to have little predictive value beyond the prediction of post-training attitudes from pre-training attitudes.

Behavior was measured by using a version of the LOFT (Line Oriented Flight Training) Worksheet developed for NASA and military applications (ref. 46). The LOFT approach was modified to better encompass the Army's crew coordination objectives and was termed the Aircrew Coordination Evaluation (ACE) Checklist (ref. 44).

Aircrew performance was measured in accordance with the revised 1992 Army Aircrew Training Manual (ATM) program of standards. The revised ATMs explicitly identified aircrew coordination tasks and prescribed crew member duties. Whereas the ATMs provide specific objective requirements for mission standards, for example, hover at a skid height of 3 ± 1 feet, the standards for crew coordination are subjective. The ATMs direct evaluators to use five criteria: (1) leadership and team climate, (2) mission planning and rehearsal, (3) information exchange, (4) workload management, and (5) cross monitoring.

Grubb et al. evaluated and iteratively developed these crew-coordination measures by working with existing UH-60 (Blackhawk) aircrews in the UH-60 flight simulator (ref. 44). Tactical scenarios were developed to meet the following guidelines (ref. 44):

1. Focus on the unit's Mission Essential Task List (METL).
2. Be consistent with the published standards in the ATM and in the Aircrew Training Program Commander's Guide (TC 1-210).
3. Utilize battle-rostered crews.
4. Emphasize crew tasks.

Sixteen UH-60 aircrews from Fort Campbell, Kentucky, served as research subjects for this development effort. After each mission scenario was flown in the simulator, videotapes were reviewed, and each crew member participated in a structured exit interview. The lessons learned from these interviews and from the attitudinal, behavioral, and performance measures collected before the mission flights were used to evaluate the effectiveness of the crew-coordination measures and to develop an exportable evaluation package for use in the field. Specifically, a comparison of the pre- and post-training performance of these aircrews revealed that the training resulted in the following:

1. Better mission planning with a shortened planning and rehearsal cycle
2. Improved communication patterns within the cockpit
3. More efficient management of critical flight tasks, using the entire crew

More important, the simulator flights demonstrated that these behavioral improvements led to a reduction in the crew-error patterns that are frequently found in aviation accidents.

Flight task	Reduction in crew error, %
Detection of system malfunction	100
Terrain and obstacle clearance	43
Transition to instrument flight	100
Instrument approach and landing	83

The end product of this research is the Crew Coordination Exportable Evaluation Package for Army Aviation (ref. 44). Beginning in FY93, this training package was approved for Army-wide implementation (including Army Reserve and National Guard aviators). Another result of this effort is the installation of video cameras in all Army training simulators to support the after-action review of crew coordination behaviors.

CONCLUDING REMARKS

This chapter began by identifying the military objectives of rotary-wing training, that is, to develop training that is increasingly effective, efficient, and responsive. The challenge of meeting these objectives is especially demanding in these times of force downsizing and budget reductions. In 1993, the Army Chief of Staff wrote that "Declining military resources and increasing military missions will require fundamental changes in the way we achieve decisive victory in the 21st century Training remains the glue that binds the Army into a force capable of decisive victory." (ref. 47)

Aviation is one of the most expensive combat arms, especially with regard to training costs. Thus, the gauntlet has been thrown and the challenge must be answered by the training development community. The human factors research programs provided as examples in this chapter demonstrate that the military rotary-wing training community is being responsive to these ever-changing training requirements. Training ideas and training hardware are being developed and empirically evaluated in order to meet the criteria of effectiveness and efficiency in rotary-wing training. New techniques and models are being applied to both the development and evaluation of training paradigms.

Recently, the DOD has been exhorted to develop "dual-use" training programs, that is, training approaches and hardware that are also applicable to civilian training goals. An example of this redirection is the call for proposals under the Technology Reinvestment Project (TRP) published by the Advanced Research Projects Agency (ARPA). This focus on dual-use training technology has the potential to benefit both military and civilian training by providing a vehicle for the joint development and sharing of training technologies.

Another example of cooperative funding and sponsoring of training research is the joint development of the STRATA research simulator at Fort Rucker. Approximately half the development and fabrication costs were borne by ARIARDA and the other half by the Canadian government in support of CAE, the developer/manufacturer of the device. Similarly, ongoing research projects in the STRATA simulator are being jointly

funded by ARIARDA and other agencies (DOD and civilian) for whom the research is being conducted.

The challenge to military rotary-wing training is substantial. The aircraft are becoming more complex and the missions more demanding; the result is changes in the kinds of demands being made on military aviators. Increasingly, aviators are called upon to be system managers rather than seat-of-the-pants pilots. Current rotary-wing aircraft commonly have some form of stability augmentation systems that aid the aviator in the control of the flight path. An example is the hover-hold feature in the AH-64 Apache aircraft. The hover-hold function can be selected by the pilot-in-command (PIC) to reduce aircraft control workload and thereby to free some of the PIC's attention to tasks other than basic helicopter control. (Hover-hold is something of a misnomer in the AH-64 since the function actually holds the aircraft attitude — in flight as well as in hover — but does not maintain a constant AGL altitude. Thus, the PIC is still fully responsible for visually maintaining aircraft clearance during hovering flight.)

At the same time, the suite of systems that must be managed when the aircraft is deployed in battle is burgeoning. To provide an example, the OH-58D Aeroscout and AH-64 Attack helicopters share the Airborne Target Handoff System (ATHS), a digital radio-based function to rapidly transmit target information between the scout aircraft and attack aircraft. The multifunction display (MFD) that operates the ATHS has approximately 180 pages of display information, all of which must be learned and mastered by the ATHS operator in order to make optimal use of the system in battle.

These 180 MFD pages devoted to the ATHS do not include the pages involved with controlling the weapons system, the horizontal situation display, the vertical situation display, the mast-mounted sight, the communications capabilities, initialization pages, or the aircraft survivability equipment. In all, the MFD makes about 300 pages of information available to the operator. To survive on the modern battlefield, the trainee must learn to effectively operate the MFD and other aircraft systems, despite sizable cuts in training budgets and in-flight training hours. And this includes the "high school to flight school" trainees who enter flight training with no college education and no prior flight or military experience.

The challenge to the military training community, brought about by the increased complexity of aircraft, systems, and missions, and by reduced training budgets, is profound. The challenge can be met by "training smarter," that is, by increasing the effectiveness and particularly the efficiency of rotary-wing training. Increased use of higher-efficiency training devices, for example, desktop and part-task trainers, low-cost simulators, and intelligent training devices, is one solution. Improved means of selecting trainees who have the greatest promise of success and better matching of trainee aptitudes to mission requirements is another. However, it is likely that the best "training-effectiveness multipliers" are still in the training research laboratories. It is to be hoped that they will be developed and fielded in time to meet the challenge.

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6 ALTERNATIVE TRAINING SYSTEMS

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SUMMARY

Emerging computer-based training methods are discussed as low-cost alternatives to current flight simulators. The history of flight simulation and of other flight-training devices is presented as a means of understanding how the industry evolved, especially with respect to the requirements pertaining to simulator fidelity — a primary cost driver. Practical applications of popular flight-simulator software developed for personal computers are described and a training system that integrates computer-assisted instruction, computer-based flight simulation, and state-of-the-art flight-training devices is proposed. A means of organizing all rotary-wing operators into a common training-related group for the purpose of maximizing their capability is suggested, and insights into the future of simulation, with emphasis on the emerging field of virtual reality, are offered.

INTRODUCTION

It is unlikely that anyone but the most provincial of flight instructors fails to appreciate the value of simulation in flight training. Even a glance at the accident statistics will support the contention that additional training and proficiency are necessary. With maintenance-related accidents almost nonexistent, it can be argued that what remains is, for the most part, accidents caused by pilot error, which is fertile ground for on-going training. It is also the case that some necessary maneuvers that should be performed in rotary-wing flight training carry unusually high risks if performed in the aircraft, yet another reason for the use of simulation.

From a business perspective there are several reasons why simulation makes sense for the helicopter operator. No facet of general aviation is so abundantly endowed with money that expense is not a concern, but for various reasons rotary-wing operators have some of the tightest budgets. The extremely high cost of operating a helicopter is reason enough to shift training from the aircraft into a lower cost-per-hour simulator. Unfortunately, the great advances in the level of simulator fidelity that have been made over the past decade have been accompanied by similarly large increases in the initial acquisition and hourly operating costs of simulators. Today, flight simulators are unaffordable for the overwhelming majority of rotary-wing (and fixed-wing aircraft) operators. Unfortunately, because of Federal Aviation Administration (FAA) mandates, it appears they will remain so for some time.

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THE PAST OF FLIGHT TRAINING DEVICES

To understand the problem, and its possible solutions, it is necessary to understand how we arrived at this point in simulator flight training. The story goes all the way back to 1929 when Ed Link designed the first such training device, one he called the Pilot Maker. The Pilot Maker, which pilots quickly dubbed "the Blue Box" because of its construction, resembled a miniature airplane; it had wings and a tail, and offered movement in pitch, yaw, and roll. A somewhat more advanced but still crude version assisted in the successful training of thousands of World War II pilots. Eventually, the Link Simulator Company was purchased by the Singer Company, of sewing machine fame. For decades after, Singer-Link dominated the development and growth of flight simulation.

Singer-Link's growth, as well as the ever-increasing fidelity of its simulators, was spurred on by a post-World War II economy that made commercial aviation practical. The airlines wanted their pilots to receive training credit for simulator time so they could reduce the number of hours that their aircraft were tied up for training. The airlines had learned early on that in-flight training could result in accidents, that it was expensive in terms of direct operating costs, and, even worse, that it took a revenue-generating aircraft out of operation. Unfortunately, during this evolutionary period of simulation, the principal designers of the simulators were engineers, not educators. The FAA was staffed with former military pilots who had, for the most part, engineering backgrounds. As a result, it should be no surprise that their design axiom became "If it looks like a bird, walks like a bird, and flies like a bird, then it must be a bird."

The FAA became adamant that a simulator had to be as close a duplicate of the actual aircraft as possible if it were to qualify for training credit. The result was a box whose interior was almost indistinguishable from that of the aircraft being simulated, perched precariously atop legs and arms that heaved, pitched, yawed, and otherwise translated control inputs into motion amid leaking hydraulic fluid and whirring motors.

The major problem with this pseudomotion was clear: it simply did not accurately duplicate the motion cues a pilot would experience in the aircraft. Moreover, it could not do so as long as the simulator was attached to the ground. But it made the engineers and the FAA proud because it was complicated, expensive, and looked very authentic. Unfortunately, the simulator cost curve began to accelerate upward toward an intersection with the aircraft cost curve. It was not long before only a privileged few could actually afford to use a simulator, let alone own one. Those privileged few included the military, which passed on the costs to the taxpayer, and the airlines, which essentially followed suit.

In the 1950s, Rudy Frasca designed and built a generic simulator. He recognized early on the fallacy of the never-ending spiral toward total simulator fidelity. He also recognized the folly of mechanically induced pseudomotion. As a result, he was able to predict the inevitable overpricing of simulator training, and he set out to build an alternative based on the simple principle that form follows function. First, thought Frasca, decide what kind of training you want to do, then design the training device to accom-

plish that training. The big simulator company engineers made fun of Frasca's simulator, and the FAA refused to let it even be called a simulator. Many in the military called it a toy, and U.S. airlines refused to even consider it. For a man with less vision, the broad negative response to his early efforts would have been overwhelming, but Frasca simply kept making and selling his little simulator. Universities and other pilot-training operators knew what these industry giants did not: Frasca's simulator worked, and it did its job inexpensively.

In the 1960s and 1970s other manufacturers began producing devices that were similar to Frasca's, and the business of generic flight simulators grew significantly as flight training programs all over the world began to include this low-cost form of flight simulation. Before long, foreign military and airline operators began buying these devices for use in their training programs. They bought them because the simulators worked and because they were unfettered by overly restricted, engineering-oriented FAA requirements.

In the mid-1980s, something happened that would forever change the "low-cost, generic flight simulator": the advent of the low-cost microprocessor. Now most of the complex gears and levers of those early simulators could be replaced with computer software and digitally driven instruments and equipment. Suddenly, there was a dramatic upturn in the fidelity with which these simulators performed because their performance became a matter of software programming rather than mechanical engineering. But now the end users, no longer content with whatever the manufacturers offered, began to dictate what they wanted in this new breed of flight-training devices (FTDs).

Software programmers became the modern heroes of simulation, and each new programming triumph was met with a demand to go on to the next step. In the beginning, software programmers were often university computer science students earning their way through graduate school. They produced remarkable results and brought low-cost simulation to heights of realism that began to approach that of multimillion dollar simulators.

But the ever-increasing consumer demand for higher fidelity, a wider array of sophisticated options, and the ability to simulate multiple aircraft with a single training device placed a heavy demand on the software programmer. This spawned the professional software engineer who began to spend more and more time refining performance and handling characteristics simply because it was now possible to do so. But these individuals commanded ever-increasing salaries, and slowly the cost of low-cost flight training devices began to creep upward. The industry had come full circle. These flight training devices were still significantly less expensive than their simulator counterparts, but they were now too expensive for most flight training operators.

Once again the industry is faced with the same old problem: those who most need simulator training are usually the ones who are least likely to be able to afford it. The FAA, for its part, issued Advisory Circular AC 120-45A, Flight Training Devices, which sets forth a system that categorizes flight training devices into seven levels. This new advisory circular primarily affords some financial relief to the air carriers who have been forced to rely heavily on full-motion simulators, the cost of which can, in some

instances, exceed that of the actual aircraft. These new devices will presumably be authorized as part-task trainers in an effort to eliminate some of the required, and more expensive, simulator time. According to Dornheim, the new advisory circular has "sparked development and sales of flight training devices" (ref. 1). But AC 120-45A treats these new flight training devices in a manner similar to the way it treats simulators; that is, it calls for training devices to have high levels of fidelity, in terms of matching the performance and handling characteristics of the aircraft, even for generic devices.

The FAA now requires the manufacturer of a generic flight-training device to first make up a complete set of engineering data for the performance and handling characteristics of the proposed generic aircraft. (Note that the generic aircraft does not exist.) Then, for initial device certification, and on an annual basis thereafter, it must be proved that the training device continues to conform to those make-believe, generic specifications. The FAA is, therefore, requiring the faithful reproduction of something that does not exist! The expense of being able to design and build a device that meets these FAA specifications, and one that can also provide a means for doing routine engineering justification, will put the cost of the device out of the reach of most flight-training operations. And to these costs must be added those of the FAA in conducting these annual inspections.

Unfortunately, in the process of developing their advisory circular, the FAA chose to ignore the almost 30 years of successful pilot training that was done in generic flight-training devices. With a stroke of the pen the FAA essentially rendered all pre-existing flight-training devices unusable (after a brief transition period). Thousands of devices at hundreds of universities, fixed-based operators, and other flight schools will suddenly become useless. Instead of looking forward, capitalizing on what we know to be true through actual pilot training experience and research conducted by credible universities, we are moving backward toward the engineering approach. Rather than the simple axiom "form follows function," we are forced to make form the goal regardless of its training value.

PRESENT ISSUES

The question at the heart of the simulator fidelity issue is how much fidelity is necessary? Must the ab initio student be trained in a high-fidelity simulator in order to learn basic aircraft control? Is it necessary for simulator systems to be exact duplicates of the aircraft in order for the student to learn systems management? Caro pointed out that it is "unlikely" that the effectiveness of the training conducted in a simulator is attributable to any single factor; more likely it is a function of the hardware, program, personnel, and other, even unknown, factors (ref. 2). It is important to bear in mind that training programs utilizing low-cost flight-training devices are not attempting to type-rate pilots. These programs utilize flight-training devices as a program enhancement and to make their actual flight training more efficient. Therefore, it is only necessary that the appropriate cause and effect relationships exist between control inputs, handling characteristics, instrument displays, and performance. This philosophy was supported by Smode and Hall who wrote:

Training devices should be concerned with transfer of training, rather than the engineering approach to simulation which believes physical correspondence with the actual aircraft is necessary. It is more appropriate that the level of fidelity required should be determined by that which is necessary to facilitate learning. [Ref. 3]

This has been supported by numerous prior and subsequent studies, including those of Povenmire and Roscoe (ref. 4), Valverde (ref. 5), and Swezey (ref. 6). There is also ample research to indicate that systems management training does not require high subsystem functional and control/display fidelity. In fact, Fisk and Jones, who studied global versus local consistency, cautioned about the potential problem of lower-level consistencies interfering with higher-level performance (ref. 7). It is possible for the student to become so focused on an irrelevant, minor aspect of the task that training in the task itself may suffer; this a strong argument for simple part-task trainers.

The idea of part-task trainers has been addressed in numerous studies. Schneider cautioned against training for the total skill (ref. 8). He identified six common training fallacies including "target task training," which contends that the training environment must be as close as possible to the conditions of the real world. This is precisely the current FAA orientation. It assumes that the real-world presentation is the best environment for learning. Ironically, though, for many training tasks, the real-world environment is not only less than ideal, it is undesirable. For instance, Hennessy et al. compared various flight simulator visual displays in training naive students to fly straight and level (ref. 9). It was determined that certain unconventional and inexpensive visual displays were more effective than the more elaborate displays for teaching some basic flight skills. Hennessy et al. also concluded that they (inexpensive visual displays) could "prove to be superior to conventional displays on a time-to-train as well as on a cost basis." Once again, we have support for the nonengineering orientation of "form follows function."

The logical extension of the philosophy of form follows function is the need for a training-task/device matrix. As an industry, we need to put the archaic idea of "the more it looks like an aircraft the better it is" behind us. A matrix should be developed that would consider the specific task to be learned, the level of proficiency to which it must be learned, and the device function and fidelity level necessary to accomplish it.

MULTIPLE PERFORMANCE CONSTANTS

Instead of using the power of the microprocessor to chase after expensive, excess simulator fidelity, that power could be better used in resolving more training-related concerns such as low-cost training devices capable of simulating multiple aircraft. Kolcum reported that one of the lessons learned during the Gulf War was the need for field-deployable, flexible-mission rehearsal simulators (ref. 10). Several companies either currently have, or are in the process of developing, devices that can simulate two or more different aircraft. One such company is developing a mission-rehearsal simulator that duplicates a C-130 cockpit and that can be reconfigured into a helicopter cockpit in about 30 minutes.

Frasca International has, for a number of years, offered training devices with generic cockpits that have up to nine different aircraft performance templates; the templates can be tailored to represent any aircraft the customer chooses. The software changes are instantaneously available through the operator's console, and conversion from single-engine to multiengine aircraft requires a hardware change that takes fewer than 3 minutes to complete. The unit can be programmed with performance and handling characteristics that are highly representative of a specific aircraft. The direct operating costs of these devices is negligible; unfortunately, the acquisition cost is not. These devices are unaffordable to all but a relatively few users; moreover, only limited effort has been made to accommodate helicopter operators. The picture may not be as dismal as it appears, however, because there is an emerging field of simulation that holds tremendous promise.

COMPUTER-BASED FLIGHT SIMULATION

One day in 1988 I happened to be talking with Stu Moment, an old friend from college and coauthor of a popular software package marketed by Microsoft and called Flight Simulator. At that time the software simulated the cockpit environment of several different general aviation reciprocating- and jet-engine aircraft including the instrument panels and outside visual displays. During the conversation we talked about the potential training value of Flight Simulator. I became convinced that it did have potential and subsequently applied for, and received, a modest grant from Bowling Green State University (BGSU) to fund an internal research project (ref. 11).

In the project, the performances of students learning fundamental aircraft control by using Microsoft Flight Simulator and a well-established flight-training device known as the Link GAT I were compared. The results indicated that definite training value was derived from the computer-based flight simulation (CBFS). This is remarkable because the cost of the software, which can be run on an ordinary personal computer (PC), is only a small fraction of the cost of a flight-training device. The study results showed that flight simulation could potentially be available to anyone with a PC!

The project caught the attention of one of my graduate students at BGSU, Brian Spitznagel. As a result, he made the use of the same software, in aiding private-pilot student understanding of electronic navigation equipment, the subject of his thesis (ref. 12). He hypothesized that the three-dimensional form of the software's display would be effective in helping students grasp the concepts. The results of his research were positive.

At approximately the same time, I began discussing these projects with Steve Hampton of Embry-Riddle Aeronautical University (Bunnell, Fla.). Flight simulator games had been a long-time interest of his, and as a result he conducted a project that favorably compared another popular flight simulator software package called Novel Twist with GAT I and Frasca 141 flight-training devices. The comparisons were made in terms of basic attitude-instrument and radio-navigation training for private pilot certificate instruc-

tion (ref. 13). Hampton continues to conduct research in the area of computer-based flight simulation transfer of training.

Another colleague, Gustavo Ortiz of Andrews University (Berrien Springs, Mich.), also became interested in my project and subsequently conducted one of his own in which he measured transfer of training from another popular software package called Elite to an actual aircraft. He too found that the inexpensive computer-based flight simulation system demonstrated positive transfer of training to the aircraft (ref. 14).

Currently, there are several researchers investigating different aspects of computer-based flight simulation and transfer-of-training issues. The question is no longer whether such a system has training value; it is now a question of which areas of flight training are best suited to computer-based flight simulation and of the extent to which it can be used. Whatever tasks computer-based flight simulation proves best suited to perform, I recommend a flight-training delivery system that integrates computer-assisted instruction, computer-based flight simulation, flight-training devices, and actual aircraft flight instruction.

COMPUTER-ASSISTED INSTRUCTION

During the early 1970s there were individuals who thought computer-assisted instruction (CAI) would replace classrooms and lecturers. Most teaching professionals, however, recognized it for what it really was: an outstanding instructional aid. The primary advantage of computer-assisted instruction is its interactive capability. It can present a large volume of standardized material including the written word, animated graphics, photographic and videographic images, and recorded sound depending on the hardware configuration. After the student reviews the material, it is possible for the computer to evaluate his understanding of the material in terms of predetermined learning criteria and, if required, direct the student to a remedial lesson to correct any deficiencies. Another primary advantage is that CAI can be used anywhere that the student has access to a personal computer and monitor. For these and numerous other reasons, computer-assisted instruction has been used by training professionals for many years.

If this appears to be rehashing old ground consider that computer-assisted instruction, computer-based flight simulation, and flight-training devices all have one thing in common: the computer. *Computer-based flight simulation* is fundamentally nothing more than a CAI system with a set of input/output devices configured to resemble aircraft flight controls. A *flight-training device* is essentially the same but with more specialized hardware to make it appear like an aircraft. The essential ingredient of all these devices is that they are software-driven. It is well within the capability of software engineers to develop the software necessary to link them all together.

Since approximately 1987 I have been advocating the development of an intelligent, interactive flight-training system composed of a computer-based flight simulation and a flight-training device. This system could meet a wide range of training requirements including ab initio, recurrent, transition, and proficiency training. Depending on

the intended application, it could represent a generic aircraft, a specific aircraft, or several aircraft with interchangeable FTD instrument panel modules. Consider the student who is about to be introduced to the task of hovering in a helicopter.

In a comfortable, quiet, well-lighted room the student sits in front of a personal computer that includes a set of helicopter flight controls. The student inserts a floppy disk containing the lesson on hover into the computer's disk drive, then types the appropriate password. The program loads into the computer, after which the student removes the learning unit disk and replaces it with a personal training disk. This training disk maintains a history of all the student's training. With the administrative tasks completed, a drawing of the actual helicopter flies slowly across the screen, hovers over a designated spot for a moment, and lands — a perfect demonstration of hover as seen from outside the aircraft.

After the brief visual demonstration of the maneuver to be learned there follows a comprehensive explanation, which includes graphics and animation. Main- and tail-rotor aerodynamics are illustrated because even airflow is depicted to show the student exactly what is happening. As the lesson progresses, the program evaluates the student's understanding of key issues by means of on-screen questions — multiple choice or short-answer — that the student answers. Incorrect answers cause the program to branch to a remedial lesson complete with appropriate graphics until the student can demonstrate an acceptable understanding of the material. At the end of the cognitive portion of the lesson, the student is given a comprehensive, on-screen evaluation of all the material, again with necessary remedial branching. Unlike the old flight instructor joke that says if the student doesn't understand something just repeat it louder, the remedial lessons would present the material in a new way, perhaps with different text, simpler analogies, and more detailed graphic representations.

After the student successfully completes the evaluation the computer then demonstrates the hover maneuver. The lower portion of the monitor displays the aircraft's instruments and the upper portion displays (for example) an outside, forward view, or perhaps a view of the aircraft as if the student were watching it from behind. A more sophisticated version might even include visual displays for side or chin windows.

As the computer demonstrates the maneuver, a very brief description of what is happening appears on the monitor or is heard over a simple sound system. The student then attempts the maneuver with the computer coaching, much the way an instructor would in the actual aircraft. Initially, it would be a perfect environment devoid of wind or obstructions.

As the student's performance improves, the computer decreases the acceptable tolerances and reduces the coaching to short prompts. When the student's proficiency reaches the optimum criteria, the program begins to complicate the maneuver by including additional variables such as wind and hovering in an enclosed area.

Once the student reaches a predetermined level of competency through practice, the program gives the student a practical evaluation. If the student does not meet the

criteria, remedial instruction and practice are provided as necessary; otherwise, the student is instructed to go to the flight-training device.

The student now inserts the same computer disks into the FTD computer which then gives a brief review of the principles of the maneuver by using the visual system to display text and graphics, and a sound system for narration. The review includes a standardized portion for all students and an individualized portion that reviews the areas of weakness that the student demonstrated during CBFS training. The flight-training device then demonstrates the maneuver, operating all the instruments, controls, and visual displays in real time with simultaneous audio explanation. In the next step, the student practices with audio coaching, then practices to build skill, and finally is evaluated with remedial instruction provided as necessary. Upon successful completion of the lesson the student is instructed to meet with the flight instructor. The instructor is able to review the student's training history on that or any other previous learning modules, before they take off for an in-flight lesson.

There are significant advantages to such a system. The interactive and individualized training allows students to learn at their own rate and with remedial help always available. The low-cost of the computer-based flight simulation allows the student to study at home, and the learning units provide for highly standardized instruction, assuring that all students learn precisely the same material and to the same standards. The system also provides a standardized, unbiased cognitive and skill evaluation. And it would be a simple matter to expand the training to include a vast array of subject matter such as turbine-engine operating principles, sling-load operations, or weather radar.

Moreover, the system provides a comprehensive training record for each student, one that can be treated like a pilot logbook, in that it can travel with the pilot. With such a system a pilot who received initial training at a flight school in Shorewood, Illinois, could make a seamless transition to training in Portland, Oregon. Professional pilots would be able to present their training history to a new employer in a form that would detail not only the subjects in which they have been trained, but how long it has been since they last reviewed those subjects.

When I originally presented this idea at the Fourth International Symposium on Aviation Psychology it was not generally well received (ref. 15). Members of the FAA said there would never be any training credit given for anything that included a computer game. Manufacturers of flight-training devices said their systems were proprietary and intimated they would never expose their software to potential competitors. Interestingly, only the developers of the computer-based flight simulator software were actually enthusiastic about both the benefit to the student and about the possibility of embarking on a cooperative effort with other manufacturers. Perhaps the most short-sighted of all were the comments from some of the flight instructors present. They accused me of trying to eliminate the flight instructor from flight training. I was astounded, because as a flight instructor I viewed this as the ultimate teaching tool that could help make my job easier. My feelings were best summed up in a recent comment by Captain Ernest L. Lewis, Commanding Officer of the Naval Training Systems Center, and noted in reference 16. He said the new technologies were helping to redefine the role of the instructor from stand-up lecturer to coach.

Four years later at the Computer Pilot's Association of America Conference held at Cornell University, I again presented the idea, this time to a group of computer-based flight simulation users and software programmers; they gave it their overwhelming support. Later that same year I again presented the idea at the Aerospace Technology Conference and Exposition of the Society of Automotive Engineers (ref. 17). The collective response from the educators and researchers present was very positive. The next year Benton et al. (ref. 18) released a report about the basic flight instruction tutoring system (BFITS) which finally brought to actuality much of the idea I had been promoting for over 5 years. By all reports, BFITS lives up to my best expectations.

VIRTUAL REALITY: ONE STEP AHEAD

Everything discussed thus far is well within the capability of today's technology. All the pieces currently exist and in at least one instance they have been integrated into a system. If all of this sounds far-fetched then I caution you to prepare yourself for what follows; it may read like science fiction, but it is not fiction. Not only is it within our technological capability, but it already exists, at least in its separate components.

Suppose for years you have day-dreamed about your ideal home. You know every inch of it by memory: the kitchen with the huge center work island, the sunken living room with bay windows looking out over acres of woodland and lake, and that fantasy master bath with separate shower, sauna, tons of storage space and beautiful whirlpool bath with a small window providing fresh air and natural light right above it. The only thing missing has been the land and the financing. Then one day the perfect piece of property becomes available and the financing can be worked out. The dream is so vivid you can almost touch it, but fantasy is a far cry from reality. You probably haven't thought about the glare from the midday sun shining through those living room windows, or how inconvenient it would be to have to reach over the whirlpool to actually open the little window, or how much room you really need between your kitchen island and the cabinets on the wall behind it. Enter virtual reality (VR) and a very progressive architect.

The two of you spend hours going over every detail of your dream home. The difference is that instead of putting all this down in the traditional paper format, your architect does all the planning on a computer workstation. When everything is programmed, you are invited back to the architect's office to view the results. But instead of sitting down and poring over blueprints you are invited to put on a helmet-like device with a small visual display for each eye and a pair of gloves.

After donning the gear, which is connected to the workstation by an umbilical cord, the architect activates the system. Suddenly you are standing in your dream living room, looking at the sun streaming through those huge bay windows; perhaps a southern exposure wasn't the best idea after all. A bit of keyboard sleight of hand and you are in the kitchen. You reach down and open a cabinet door only to discover that it nearly touches the center-island work station; you definitely need more floor space in the kitchen. The architect increases the distance by making keyboard entries and suddenly there is plenty of room between the two, as the computer subtly rearranges the entire house floor

plan to accommodate the newly enlarged kitchen. It is not difficult to imagine the possibilities of such a system, and it is only in its infancy today; the potential for tomorrow is beyond imagination.

The helmet and gloves are simply computer input/output devices. The helmet is a miniature visual system that also relates head movement to the appropriate view within the virtual environment. Each glove is essentially a very sophisticated mouse which also relates hand and finger movements to the virtual environment. Already, researchers have produced helmets with sophisticated sound and visual systems that can very precisely input relative head motion to the computer to update the virtual-environment point of view. In fact, the helmet and gloves are so common that less sophisticated versions have already become commonplace in the world of video games.

There are also prototype body suits and advanced gloves that not only serve as input devices to the computer but also act as output devices to the wearer. A system so equipped allows the wearer to move freely within the virtual environment, opening and closing doors and windows, turning lights on and off, hearing representative sounds, and feeling representative pressures against the hand and body. If, for instance, the wearer reaches out and turns a doorknob, not only will the door open but the glove will provide appropriate feedback and the wearer will "feel" the doorknob as a solid object. To someone observing this from the real world it would appear as if the person is simply walking about the room, reaching out into space, and turning his hand.

What does all this have to do with rotary-wing flight training? Everything. It has the most profound training implications in history. First and foremost, because all the hardware involved in a VR system is standardized, it reduces all simulation to a matter of software development. That simple fact alone will permit a dramatic reduction in the cost of training. It will ultimately allow the development of highly customized training environments that will duplicate a specific aircraft by serial number, and that will allow training to take place anywhere there is electricity.

A virtual-reality flight simulation could include all of the training elements of the integrated computer-based flight simulation and flight-training device system but in a far more sophisticated form. It is important to note that a VR simulation still will not replace the flight instructor; it would simply be a very sophisticated training device. But what a training device!

Imagine this scenario. The chief executive officer has plans to pick up his congressman at New York's La Guardia so they can both attend an important meeting at the World Trade Center. He wants to use his new corporate helicopter based on the East Coast and have it flown by his two favorite pilots. Unfortunately, neither pilot has ever landed at the World Trade Center heliport. One has never flown other than in the Los Angeles basin; the other is stationed with the aircraft in Boston and has never met his copilot for the trip. A bit contrived, but for the sake of argument let's look at how a VR system could help the pilots prepare for the trip.

The pilots go to their respective flight operations offices in Los Angeles and Boston at a prearranged time and don their VR training suits. Connected by modem to a common computer, they select the correct aircraft option, choose left or right pilot position as appropriate, the New York environment data base, and the latitude and longitude coordinates for the area at La Guardia to and from which they will operate. The pilots then find themselves sitting side-by-side in what, for all intents and purposes, appears to be the aircraft with La Guardia airport visible outside the windshield. They can talk to each other, go through the checklist and engine start, and work the flight as if they were really there. Even air-traffic control (ATC) simulators are being developed that could one day provide realistic air-traffic conflicts and reports. The pilots could polish their crew coordination, work under varying meteorological conditions, and become familiar with both terminal environments.

Sounds too fantastic? Watch television some evening. When you find yourself asking how the advertiser performed some feat of apparent magic, like a balloon transforming into a car that drives away, answer computer graphics. Someone created the entire sequence with a computer and the rendering is so perfect that you cannot tell the difference with the human eye. It is created with software in the same way as virtual reality; in fact, it is virtual reality. It only requires a computer workstation, some standardized VR input/out devices, a lot of dedication, and time.

You see, now that we have reduced all of this to software development, it only takes one person obsessed with the idea of developing the perfect Bell 412 simulation to make it happen. Perhaps it will be a software engineer working for a progressive simulator manufacturer, or perhaps just a 412 pilot who happens to be a computer junkie. And when that one is done, someone else will rise to the challenge and create the perfect S-76, and so on. One way or the other, it will happen, simply because the means to accomplish it exist. It will evolve just as surely as did computer games, computer-based flight simulation, and other high technology miracles. Unfortunately, its evolution will certainly be hampered by many manufacturers and, no doubt, by the FAA itself, as self-proclaimed simulation experts stand by slack-jawed, unwilling to accept the future. Sadly, it is human nature to cling to what we know, that in which we perceive the safety of familiarity.

In 1899, Charles H. Duell, Commissioner of the U.S. Patent Office, recommended to President McKinley that the Patent Office be closed because everything possible to invent had already been invented. He failed to see that *when men are free* there will always be a few farsighted and creative individuals who are willing to take risks and to take the best of the past and forge it into a better future.

CONCLUSIONS

Unquestionably, the designers and manufacturers of flight simulators have devoted far more of their attention to fixed-wing aircraft than to rotary-wing aircraft. The reason is a matter of supply and demand. If rotary-wing operators demanded, and could afford, more simulation, the manufacturers would happily oblige, and the FAA would issue a flurry of advisory circulars, regulations, and other paperwork. Unfortunately, most ro-

tary-wing operators are too small to be able to afford the expense of contract simulator training let alone buy their own simulators. If ever there was a field ripe for organization, this is it.

I believe a consortium of rotary-wing manufacturers, insurers, related special interest groups, and operators should be organized to represent the training interests of all rotary-wing operators. The consortium would survey all operators and establish priorities that would address the training needs of everyone. A system such as I have proposed could be developed for the most common aircraft to begin with, but with the goal to develop units that could be quickly reconfigured to represent different types of rotary-wing aircraft. Participating operators would be able to purchase the computer-based flight simulation software for their local operation, and compatible flight-training devices could be set up in regional training centers. These centers would be subsidized by the consortium so that the hourly training costs would be kept to a minimum for consortium members. As an alternative to the training center, flight-training devices could be installed in trailers and moved to scheduled locations throughout a given region. The operators would have the option of scheduling training to coincide with the flight-training device's arrival in their area or arranging for their pilots to receive training at other scheduled sites.

The consortium would also be the appropriate group to spearhead the effort to develop appropriate emerging technology, whatever form it takes, for the purpose of making better and more cost-effective training alternatives available to all rotary-wing operators. Historically, helicopter operators have received short shrift. It is true that some changes are under way, but they can be expanded, expedited, and implemented only if the operators of rotary-wing aircraft stand together in their demands to the simulator industry and to the regulatory agencies.

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7 TRAINING DEVICE MANUFACTURING

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SUMMARY

The role of the manufacturers of flight training equipment in the field of rotary-wing aircraft flight-crew training is described. It draws upon the experiences gained in both rotary- and fixed-wing simulation in which the aim has traditionally been to duplicate the flight deck and its functions and to provide the best compromise in motion-cue and visual-scene presentation. This enables a trainee to practice both normal and abnormal procedures in a highly realistic environment under the supervision of an experienced instructor. Unlike the actual aircraft, however, this simulated environment is tolerant of pilot errors, enabling flight envelope limits to be safely approached and experienced. Moreover, maneuvers can be practiced in a simulator that are either unacceptably dangerous in the aircraft or that require flying conditions that do not prevail at the time of training. More recently, systematic training analysis and performance validation have demonstrated that valuable training and checking can be effectively carried out in a training device that is considerably simpler than the traditional high-fidelity simulator. As a result, the manufacturers of training devices have become more closely involved in understanding the training activity for which their devices are intended, thus ensuring that the equipment is not only comparable to the aircraft but is also appropriate to the training requirement. Because the manufacturers of flight training equipment must ultimately report to their shareholders, this chapter also considers some of the economic factors that contribute to the decision to develop, market, and manufacture training products to meet the needs of specific market sectors.

INTRODUCTION

The history of the rotary-wing aircraft flight simulator, the ways in which it has recently developed, and its future potential are presented from a manufacturer's perspective. It should be clearly understood that the simulator manufacturer is seldom the operator of the equipment and that his view of the subject is often constrained by his perception of the realities of the situation. These realities include the design, manufacture, and delivery of a device meeting a schedule and a customer's expectations. It has become obvious that

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the manufacturer should take a broader interest in the entire training process and, in particular, in how the device may be used in real training. In this way, the design may be better optimized for its purpose, which will inevitably expand throughout its life cycle.

From a commercial perspective, the manufacturer has to be able to make a reasonable profit in order to justify the development of rotary-wing training devices. This issue is worthy of some discussion because it places many practical constraints on both device capability and the training that can be economically provided to potential pilots. It can be argued that the entire character of helicopter training philosophies and programs can be influenced by the ability of training equipment manufacturers to provide appropriate equipment.

We shall describe how existing and future operational processes have a key role in controlling the design and operational character of the training equipment. It is very important to be aware that although fidelity of environment and the science of simulation are fascinating subjects and challenges in their own right, there is also another set of challenges associated with building a commercial product: a commercial product has to meet customer needs and must be available at the right price at the right place at the right time.

The demands that a customer-focused culture places on engineering practice to provide a commercial product are particularly relevant to helicopter simulation. The commercial environment in which helicopters are used is not only unique but it also varies enormously. This environment is radically different from that of the large commercial airlines and air forces of the world. The latter environments are familiar to the prime simulator manufacturers, whose organizational characters have evolved from the airlines and the air forces they serve. Helicopter operations are different: perhaps the most forceful examples of these differences are highlighted by the facts that commercial helicopters average fewer than 2 hours flying per day, and that the average purchase price is about \$430,000 per unit. Commercial airlines pay a great deal more per unit, which is the main reason they work to have that asset flying (usually) well in excess of 10 hours per day. As a consequence, it is reasonable to say that the unique helicopter operational environment is not very familiar to the prime fixed-wing simulator manufacturers. This environment could be regarded as presenting a different challenge to those manufacturers; certainly, it is a different market with its own set of special customer needs.

BUSINESS PERSPECTIVE: MARKET POTENTIAL FOR TRAINING DEVICES

How does a manufacturer go about assessing market potential for rotary-wing training simulators? There are two starting points for the analysis.

The first step in the market-potential analysis is to conduct an assessment of the predicted volume and value of rotary-wing aircraft sales, based on forecasts published by the helicopter manufacturers, industry analysts, and market research organizations. This helps the manufacturer to focus on aircraft types that are predicted to have large sales volumes or long periods of production or both. These are the types that may be of most interest from a training-equipment manufacturing point of view, for they may need to be supported by a significant number of units of training equipment. In addition, this helps the training-equipment manufacturer to plan production time scales to correspond to likely equipment demand peaks. This includes preparation needed to design training devices for rotary-wing aircraft types that are not yet in production.

The second step is to conduct an assessment of training and checking requirements mandated by the regulators, including proposed regulations and changes. This information enables the manufacturer to decide on training equipment fidelity, data, and equipment capability criteria that may be applicable to the training programs of all operators subject to such regulations. This assessment is particularly important in the case of a new or rapidly developing market, where changes in requirements will occur with time.

Historically, the manufacturers have been involved in the development of regulations concerning the technical performance of commercial aircraft simulators. This enables their perspective to be taken into account, and gives the manufacturer reasonable lead time in which to prepare for any impending change in regulations that may concern his products. The focus of activity has been on the fidelity of simulated aircraft handling and visual cues. The goal has been the absolute engineering duplication of the aircraft, with extensive use being made of aircraft parts and data.

Let me note that what follows in this paragraph cannot be overemphasized. It is of extreme importance to many of the issues addressed within this chapter and throughout this volume. Until recently, the manufacturers have not been closely involved in the development of regulations concerning training tasks and the assessment of the competence of trainees. *This activity is essential to us, because it enables us to develop training devices that are engineered for the training application, rather than engineered as copies of the flight deck.* This is particularly relevant for rotary-wing aircraft, whose initial and life-cycle costs are dramatically lower than their fixed-wing equivalents. These differences in purchase cost and operational cost immediately prejudice the opportunity for purchase of a simulator designed, built, and priced to the standards associated with fixed-wing equipment. However, the training requirement may mandate the use of simulation technology that is extremely advanced but that is simply unavailable at low cost.

The challenge will be to produce training equipment with standards of fidelity that can be proved to be appropriate to the training requirements for which it was de-

signed, thereby removing a significant part of the costs traditionally associated with a fully functional fixed-wing simulator. Alternatively, analysis of the requirement will inevitably show that many training and checking activities can be done at locations removed from the high-fidelity simulator, thus reducing the need for training time on the most expensive equipment. Both of the above situations have occurred in military training programs for many years. The military training optimization process is currently being adapted and applied to commercial fixed-wing applications through the development of the Advanced Qualification Program (AQP) by U.S. operators and by the Federal Aviation Administration (FAA). Recent experience in this area has shown that the use of high-cost simulation equipment can be reduced by careful study of the training requirements.

In addition, analyses of flying incidents have shown that about 70% of them were caused by human error, rather than by inadequacy in the traditional flying skills. On this basis, the AQP process is changing the focus of skill development to ensure that crew behavioral issues are addressed. The emergence of crew resource management (CRM) training and assessment in line-oriented flight training (LOFT) and line-oriented evaluation (LOE) is changing the character of training requirements. This is having an effect on the specification of training equipment, which to date has been used only for the development and assessment of the traditional flying skills. This new paradigm can be expected to be adopted by the rotary-wing training community.

The definition of the training and checking that have to be carried out as a prerequisite to pilot certification is critical to ensure that the manufacturer has gauged the market adequately. This point is best understood by looking at the situation that exists for large jet transports: current regulations combined with operational costs make training and checking using a simulator and associated equipment the most cost-effective option for an operator. The sales volume of training devices is not simply a result of the number of operational aircraft. It relates also to the amount of time that the training equipment is used by each crew member. If large numbers of training and checking hours are required, the operator may have reason to purchase equipment rather than hire time on somebody else's equipment. For example, a mature B-737-300 fleet of 35 aircraft may generate a demand for traditional recurrent training and checking in full-flight simulators of between 3,000 and 3,800 hours per year, which would require two to three training slots of 4 hours per day; the operator might find that this demand volume would justify the purchase of a simulator. This example highlights the need to understand how much training demand there is, how heavily utilized the equipment may be, and, consequently, how many purchases are likely to be made by an operator.

As indicated above, a key issue in determining full-flight simulator market volume is the extent and frequency of recurrent training and checks. If regulations do not

force operators to train and check to comparable standards to ensure adequate safety margins, there is little incentive to consider the purchase of a simulator, especially if fleet sizes are small. For large jet transports, the alternative approach of training and checking in the aircraft itself is not cost-effective. This is not so for very small aircraft, which are frequently used for training. However, the extent and thoroughness of the regulatory system covering the large aircraft extends to training maneuvers that simply cannot be practiced in the aircraft itself — wind shear being the best example, with other adverse environmental conditions being generally unavailable when needed for a training flight.

When regulations have not been developed to ensure the highest standards of flight safety, it is difficult for the manufacturer to estimate the potential demand for training devices. It is highly likely that operators of rotary-wing aircraft will carry out most training by using the aircraft, and that only the largest centralized organizations will consider synthetic training aids as being worthy of consideration, especially if those aids are priced at levels more appropriate to a multi-engined, wide-body full-flight simulator. This is the environment of the "one off" training device, for which the manufacturer has a relatively poor opportunity to amortize his one-time costs over a significant run of repeat orders, which would enable him to get costs down and still return an acceptable profit to the shareholders.

With military applications, the perception of the role of training is different from that held in most commercial operations. In particular, the military requirements that maneuvers be carried out at the limits of the flight envelope and close to the ground, and that full-capability military missions be conducted with highly sophisticated weapon and electronic systems, impose a rigorous design approach on the manufacturer, one that pushes simulation engineering to its technical limits. Although this kind of approach inevitably includes a great deal of one-time engineering, it is clear that a significant proportion of the design work can be applicable to other projects.

On the basis of the above, the manufacturer will decide how to approach the market, making key decisions concerning product specifications, appropriate price ranges, and segmentation issues such as high- and low-end products and regional distribution of sales.

At this stage it is conceivable that the desired product is unattainable for the estimated price that the market will bear. It is also possible that the predicted number of equipment unit sales, when taking estimates of market share into account, will be insufficient to cover the one-time investment in design, development, and tooling necessary to produce the equipment.

Cost breakdowns for the proposed product will disclose critical issues concerning fixed material costs (especially aircraft parts), and break-even volumes required for

making or buying components or services. Integration of the time required to order and produce components, subassemblies, and the complete product will also disclose important issues. The above activities simply give a flavor for the complex processes that take place during the early stages of design; some of these will be covered in more detail later in the chapter.

It is important to realize that the "go/no go" decision for a product may be reassessed at many stages of the above activities. It will also be assessed during the life cycle of the product, especially as costs change owing to external factors (e.g., exchange rates and inflation) beyond the control of the manufacturer.

Changes required to keep the product's specifications current with aircraft updates may be significant, especially during the early life of an aircraft type. This affects the experience curve, and as a result, truly optimized repeat products may never be achieved.

On top of all of the above points, there is the issue of competing with other manufacturers. Free market competition practically ensures that the customer gets the best deal. However, competition between manufacturers specializing in full-flight simulators is so fierce that profitability is being eroded. There is little incentive in such an environment to enhance technology further to provide extra levels of realism unless it can be explicitly demonstrated that the manufacturer will financially benefit, either through increased market share or through reduced manufacturing costs. The only other way to justify product enhancement is through an explicit demonstration that use of the device enhances training value, in the eyes of the customer. This situation has come about at a time when the levels of simulation have exceeded regulated minima, and when the high levels of the fidelity and sophistication required for effective training (particularly during the early stages) have been questioned. In short, the market and supply industry have matured.

This is the world of the manufacturer (and of all businesses): unless it can be done profitably, it will not be done. The market defines the acceptable price.

We shall now consider at a top level the business prospects for rotary-wing simulation for training and checking through to the next century.

Analysts expect new helicopter deliveries to average about 500/year between now and early next century with growth from the present level of about 400/year to about 550/year in the next century (excluding piston-engine types). At no point are sales levels expected to approach those of the early 1980's, when deliveries exceeded 800 units per year for four consecutive years, with a peak of more than 1200 in 1981.

Piston-engine types are frequently excluded from market analyses primarily because of their diversity and low value. However, certain piston types have been remarkably successful, such as the Robinson R.22; however, by early in the next century the proportion of piston-engine helicopters in service will have been reduced by about half. Market segmentation by type is generally on the following basis (from 1991 data):

Type	Number	Percent of total	Percent excluding light piston
Light piston	503	46	—
Light single turbine	353	32	60
Light twin turbine	85	8	14
Intermediate	135	12	23
Medium/heavy	6	1	1

It is worth looking a little more closely at these potential sales. Taking non-piston types, 337 units were delivered in the United States in 1992; they had a value of \$146 million. This equates to an average unit purchase value of about \$430,000, excluding the cost of logistical support. The more expensive helicopters are valued well above this; for example, the Super Puma costs between \$5 million and \$6 million. From these figures it is clear that a simulator manufacturer must gear the pricing of his training equipment accordingly: current prices for a fixed-wing aircraft corresponding to a Boeing B737-300 are of the order of \$30 million to \$35 million, and a simulator for that aircraft would cost about \$10 million. The approach taken above is well understood by the prime training equipment manufacturers, but comparison with turboprops is perhaps more appropriate: a Dash 8 for \$12 million, a Brasila for \$7.5 million.

Taking the U.S. figures a little further, during 1992 it was estimated that 6,300 helicopters were operational in the United States, including piston-engined types. Together they flew approximately 2.8 million hours, which equates to about 440 hours per helicopter, for an average of about 1.2 hours flying per day. However, about 3,800, or 60% of the helicopters are turbine-engined, and these flew 2.2 million hours, or 79% of the total, averaging around 1.6 hours flying per day, more than double the workload of the piston-engined flying time of 0.7 hours per day. Even so, these utilization figures do not compare well with those of the average large jet transport, which may be flying well

in excess of 10 hours per day, when aircraft availability owing to weather, downtime, and crew availability is considered. An important point can be made here considering the potential volume and value of training equipment: whereas the value per unit (of a simulator) is low compared to that of a fixed-wing aircraft, it is relatively high compared to that of a rotary-wing aircraft. Consequently, it may be easier to justify the cost of a simulator for a high-cost, fully utilized fixed-wing aircraft than for a relatively low-cost, only partially utilized rotary-wing aircraft. The significance of this is that the cost of training in the fixed-wing aircraft might be prohibitive, but training in the under-utilized rotary-wing aircraft it might be cost-effective.

An implication here is that the conventional approach to simulating large commercial and military aircraft is not appropriate to the commercial rotary-wing training market. This statement can be made purely on the grounds of cost and utilization. Market development must take these factors into account, requiring a radical realignment of approach by the simulator manufacturers to develop a successful product. This is notwithstanding the fact that the sophistication of helicopter simulation is considerable, as the remainder of this chapter will bear out. There currently exists a gap in expectation, and it is unlikely that a change in regulations imposed on operators in the interests of safety will eliminate that gap.

There is clearly an opportunity to develop alternative approaches to the specification, manufacture, location, and use of training equipment associated with the publication of the FAA (Advisory Circular) AC 120-63. Undoubtedly, the use of sophisticated computer based training (CBT) and part-task trainers may be more appropriate than a high-fidelity, full-flight simulator. The helicopter itself may continue to be the ultimate checking environment, together with being used for some training that cannot be covered on a part-task trainer fitted with simple visual and motion systems. *The manufacturer has to consider these approaches rather than simply assume the need for high fidelity.* The nature of the helicopter transportation business and its costs make the low-cost approach inevitable.

A cursory examination of the requirement for high-fidelity simulation with fixed-wing aircraft reveals an important paradox relating to the use of synthetic training equipment for rotary-wing aircraft. The fixed-wing, high-fidelity requirement relates primarily to takeoff, approach, and landing, maneuvers that require both psychomotor and cognitive skills. Most commercial full-flight simulators for fixed-wing airline operations have been used primarily to train these maneuvers, for which high-fidelity cues are critical *because the aircraft is close to the ground.*

Lower-cost, lower-fidelity training equipment has been used principally to train for procedures and to practice maneuvers that do not take place close to the surface, other than when the aircraft is stationary. Many of these procedures do not require a fully

integrated high-fidelity flight deck. This is particularly the case in the early stages of training, when emphasis is on applications of system knowledge in the initial phase of skills development. Further, many aspects of modern aircraft operations require cognitive skill development related to interacting with and interpreting electronic-flight-information-system (EFIS), autoflight, and flight-management-system (FMS) data, all of which can be trained effectively in part-task trainers.

Affective, or "soft," skill development begins when crew members are paired in training; consequently, CRM training can also be conducted in a part-task trainer and in the classroom. Also, despite LOFT and LOE requiring high levels of psychological fidelity, particularly for the external environment (i.e., air-traffic control), there is virtually no requirement for motion or visual cues other than at the beginning and end of a flight leg scenario. Rotary-wing operations, on the other hand, are conducted, for the most part, close to the ground with an emphasis on psychomotor skills; as a result, the physical fidelity requirement is considerable.

Here is the paradox: flying conditions indicate that a sophisticated training device or the rotary-wing aircraft itself may be needed for a large proportion of traditional rotary-wing training and checking time, but the helicopter business is such that a conventional high-fidelity training device is generally not economically feasible. Low-cost equipment such as CBT and desktop simulation systems can provide cost-effective training solutions when used appropriately in a rotary-wing training regime. In addition, a radical reappraisal of the utilization and location of high-fidelity simulators in particular may provide alternative opportunities within the marketplace. The classic example concerns locating high-fidelity devices at the aircraft manufacturer's site, which acts as a focal point for initial-type training.

Manufacturers of rotary-wing aircraft see limited growth prospects for the commercial market. They are in an extremely competitive environment characterized by excess production capacity and a saturated market in many segments; this will probably lead to a rationalization of manufacturers. This gloomy outlook is compounded by the prospects of Russian export of its military and former military rotary-wing capability. Currently, these suppliers are enthusiastically promoting their low-cost equipment with increasing levels of professionalism. The end of the Cold War has affected growth prospects for military rotary-wing aircraft, with many expected orders being cancelled or down-scaled. Further, many military rotary-wing aircraft are being retired and finding their way onto the commercial market; it is anticipated that this will further squeeze the sales of existing suppliers.

Considering regional segmentation in 1993, we have the following breakdown by geographical areas.

Region	Number of helicopters	Percent of total
N. America	11,200	54
Australia	1,200	6
Middle East	200	1
Far East	2,000	10
Africa	650	3
S. America	950	5
Europe	4,200	20
Central America	200	1

The main areas of growth have been identified as Southeast Asia, the Middle East, and South America. These regions will provide the greatest opportunity for training equipment sales. In the more mature market areas, changes in regulations and operating costs will be required before there can be an increase in sales of training devices.

The military segment of the helicopter population is not considered here in detail; note, however, that of the 11,200 helicopters flying in North America, about 55% are in commercial use.

To finish this consideration of the potential market for helicopter training, a brief coverage of helicopter life-cycle costs is useful. To justify the procurement of expensive training equipment, an operator has to be able to work out his operating costs and the effect that training and training-equipment procurement will have on them over time. The FAA has expressed concern that U.S. helicopter operators do not have a highly detailed understanding of their costs, and is carrying out work with the industry to address this point. At some stage in the future, the feasibility of training by using synthetic equipment may be reappraised, but the equation will require more attractive offerings from the manufacturers, and offerings packaged more creatively than they are at present.

TECHNOLOGY PERSPECTIVE: CREATING THE TRAINING DEVICE

There are major issues involved in rotary-wing simulation and training that are different from those associated with fixed-wing aircraft. They have to do with the normal operat-

ing environments of rotary-wing aircraft, the complexity of the rotor simulation, and cost constraints. The following discussion focuses primarily on high-fidelity simulation techniques, for this gives an important insight into the complex issues involved in creating a sophisticated training device, one that clearly provides the ideal environment in which to check demanding maneuvers close to the ground.

Rotary-wing flight generally implies frequent operations close to ground. This implies that the simulator should convey appropriate realism in its presentation of the out-of-window scenes, providing coverage of the total field of view that affects visual cues. It also means that the motion cues arising from airframe accelerations and attitudes, as well as the vital vibration cues, must be simulated to a high standard of authenticity to ensure that effective training can be provided.

The challenge faced by the simulator manufacturer in providing appropriate pilot cues through realistic simulation of the rotor dynamics is well known, and various techniques are available for approximating the complex behavior of the rotor. It is important that simulation fidelity be maximized, in order to preclude any undesirable "negative training" effects that poor simulation can induce. This defines a lower level of acceptable fidelity: artifacts are unacceptable. As a result, the simulator manufacturer must use a blend of science, mathematics, and art in order to achieve the desired goal of total illusion.

TRAINING DEVICE DEVELOPMENT: FROM YESTERDAY TILL TOMORROW

Rotary-wing training in simulators is still in its infancy compared with the maturity of its fixed-wing counterpart. This is incongruous when one considers both the number of rotary-wing aircraft in service and the amount of flying that takes place close to the ground with important visual, control, vibration, and motion cues. The simulator manufacturer might argue that these provide the very reasons why rotary-wing training in simulators is so important. Where better to practice for normal and emergency situations in complete safety with all environmental conditions under control?

Yesterday

For perhaps 20 years, the flight simulator paradigm has been a facsimile flight deck mounted upon a hydraulically actuated motion system with a synthetic out-of-the-window view. The trainee pilot was expected to use the flight-deck equipment and controls in the same way as in the "real" aircraft; hence, the simulator provided a means to prac-

tice flight techniques in complete safety under the watchful eye of the training instructor. This paradigm has implicitly assumed that a faithfully duplicated flight deck and environment constitutes the best place in which to train. However, this assumption has been comprehensively invalidated, primarily through military training research. The ultimate training-related activity has become the proficiency check covering critical maneuvers carried out under abnormal operating conditions in a zero flight time (ZFT) environment. This now-routine operation can result in the certification of aircrews transitioning from one aircraft type to another without carrying out critical training and certification activities in the aircraft. In this context, the conventional flight simulator paradigm is appropriate, representing a match with the aircraft to agreed upon and certifiable standards. However, it should be noted that in many cases only 25% - 50% of transitional training is carried out in the simulator. The remainder of the training involves the classroom, computer-based training, and the part-task trainer (flight-training device (FTD) or fixed-base simulator).

In practice, the standards of simulation have always been driven and limited by the available technology. Simulation itself has helped to define and shape the technology in many areas including electronics, computing, servos, image generation, and optics. The regulators of aviation training have wisely been instrumental in setting flexible, pragmatic goals in terms of the required technical performance of the training devices. It is not, however, the equipment that trains; it is the instructor plus the equipment. Training-device manufacturers sometimes need to be reminded that the devices they strive to produce are worthless unless they are used effectively and carefully as part of an integrated training program. It is relevant to observe that experienced line pilots do not regard simulators as technical achievements; rather, they behave as though the environment is real — the smell of fear and sweat on the flight deck of a simulator *is* real.

The first commercial and military rotary-wing flight simulators were developed by applying existing techniques used for fixed-wing devices and then adding features representing rotor-dynamics and other rotary-wing-specific aspects. The core of the simulation was a real-time model of the aircraft and its systems that was reiteratively computed in response to an ever-changing set of input commands from the flight-deck controls and equipment. The outputs from the simulation models were used to drive motion and visual systems and instrument displays providing the appropriate responses to the crew's inputs.

This technique has been developed to provide a high degree of realism in many aspects of rotary-wing simulation. As cost-effective computing power increased, simulation fidelity burgeoned. At the same time, the sophistication of digital control system technology fitted to the aircraft has increased enormously. The continual advance of the control technology has, until now, prevented significant utilization of more cost-effective computing power. Many would say that in some respects simulation techniques and

fidelity even began to approach reality; however, certain areas of the simulation were always somewhat deficient.

Simulation fidelity has always depended on the completeness and accuracy of the simulation models. These real-time models are intended to be an "analog" of the actual aircraft and subsystem behavior. In practice, commercial pressures have resulted in models being developed and used that are not simply best efforts in an absolute sense, but that are constrained by the need to meet a budget and schedule. These models rely on their mathematical structure and the numerical accuracy of their coefficients in order to represent all the salient performance and operational features that are perceptible to the flight crew. "Simulator data" provided by the airframe manufacturer and engine and equipment suppliers enable the simulator manufacturer to develop these real-time models and to populate the equations with appropriate coefficients. The reiterative solution of these equations provides the response and performance of the simulator to the trainees' inputs. The data have sometimes been difficult to obtain, and poor simulator performance can sometimes be traced to their lack. Despite these limitations, it is important to note that many simulators are in daily use that were designed and built as long ago as 20 years. Statistics on incidents that involved handling skill deficiencies are evidence that the capabilities of these older, lower performance simulators have been adequate to meet the training needs.

The performance of rotary-wing aircraft has historically been rather difficult to model, the very nature of rotary aerodynamics being somewhat difficult to describe. This has challenged the simulator manufacturers and data providers for many years. The onset of localized blade stall, the transition from powered to autorotative flight, the onset of the vortex ring condition, and the rotor in-ground-effect being four situations in which mathematical models may be insufficiently complete to fully describe the real-life events. These are key areas where realism in control feel and general handling qualities can provide trainee pilots with the experience of important operational cues. Similarly, the modeling of the ground dynamics of the machine has also stretched the simulator manufacturer's abilities. It may be perceived that there has never been a completely satisfactory model for describing on-ground behavior where the gain terms due to gear stiffness are much higher than when in flight.

The overall impression might be that yesterday's rotary-wing flight simulators only partially did the job. They provided a level of simulation of the aircraft systems that seemed to meet the training needs of the day; however, their ability to duplicate realistic flying performance in any situation other than steady states, away from the extremes of the flight envelope, was limited. For this reason, their main role has been to provide training for instrument flight rules (IFR) conditions and general systems management. This situation may have been acceptable in the past, but operational requirements for better training devices now exist and are being met.

In the event that an existing simulator fails to meet expectations, the operator could specify an updating of the performance of the device. This could include any one of a number of simulator aspects that time has left behind. For example, the motion, visual, or controls subsystems may require upgrading to provide more realistic cues by using newer, more sophisticated technology. Alternatively, there may be a desire to enhance the handling characteristics by implementing a more advanced rotor model. This may in itself necessitate a new or extended computer system to provide the required computing power. Another candidate for possible upgrading might be the instructor's operating station, where technical advances can be used to help reduce the instructor's workload by providing a more effective interface. Changes over the years in the more sophisticated rotary-wing aircraft may have been so extensive as to render the simulator functionally obsolete, or partly so, requiring that the simulator be upgraded accordingly.

Today

For today's flight simulators the main aim is to radically minimize their acquisition and life-cycle costs while continuing to provide appropriate fidelity. This will help to guarantee the acceptability of training devices to cost-conscious operators while fulfilling the manufacturer's aim, which is to contribute toward better training effectiveness and to increased safety in real-life operations while maintaining an acceptable profit margin. As mentioned earlier, this point is crucial to the manufacture of rotary-wing simulators.

Life-cycle costs can show up in many areas of simulator operations. In addition to initial procurement and money costs they may also include the ongoing running costs of power, the operating costs of staff and buildings, the cost of supporting a spares inventory, and the loss of training time when things go wrong. More important, they may also include the hidden costs of undertrained personnel and the costs of using a real aircraft for training when a simulator could be more appropriate. This is particularly important when it concerns the operation of more expensive rotary-wing aircraft carrying significant numbers of passengers. Frequently, the operational environment is so hazardous as to cause a reappraisal of the economics of simulators; for example, offshore operations in severe weather.

To be practical, a trainee must be able to place his trust in the simulator when he practices all kinds of normal and emergency procedures before flying the actual aircraft. There must be total confidence in the authenticity of the simulation. This in turn leads to the fundamental importance of integrating complete and accurate simulation design data into the product to ensure that no negative or false training cues are introduced.

Design data provide the simulator manufacturer's design staff with the understanding of how the aircraft and its subsystems function so that adequate provision can be

made for simulating normal and abnormal aircraft operations and realistic integrated responses to instructor-initiated malfunctions.

The essential data take the form of aircraft wiring diagrams and schematics, loft drawings, maintenance manuals, operations manuals, system descriptions, avionics system descriptions, and interface control documents plus documents produced by the airframe and equipment suppliers specifically for the simulator manufacturers. The sum total of this information, together with the aircraft operator's knowledge and the simulator manufacturer's experience is what makes it possible to create the basic device in the first place. Typically, steady-state situations are adequately described; it is the transient and dynamic conditions, which are necessary in order to allow type-specific handling skills to be acquired, that are much more difficult to capture in a usable form.

In order to provide a realistic environment, specific information is required on sound and vibration characteristics, including the events that give rise to changes in the characteristics of each component. The audio frequency data are ideally provided in digitally recorded form for analysis and use by the simulator manufacturer. From these data, sound and vibration characteristics are synthesized in real-time, using digital computing techniques.

Analysis of the recorded sound data yields the most significant components of the sounds that are linked to the parameters responsible for their existence and variation. For example, the major engine compressor and turbine whines are identified and then synthesized using digital wave-form generators. The frequencies of the whines are controlled by functions of shaft speed from the power plant simulation model. The amplitudes of the whines are computed as functions of engine power output, so that both the frequency and amplitude vary realistically, dependent on how the engine is performing. The sounds for each engine, if appropriate, are computed separately. Similar techniques are employed to create gearbox, transmission, and rotor-drive sounds. Their levels are modulated by functions of the power being transmitted.

The rotor-blade sounds are created and "chopped" to coincide with blade-passing frequency. The levels of rotor-blade sounds must be modified by the maneuver and crosswind conditions that occur as the simulated flight progresses. Other sounds are also created to provide any aircraft-specific system sounds such as air blowers and rotor brakes. Audible sounds associated with touchdown, originating from the landing gear, are created at the appropriate moment, with the amplitude being some function of touchdown rate or severity.

The aural characteristics are recreated by using powerful amplification and loudspeakers that provide a sound level at the flight deck that is broadly equivalent to real life. The loudspeakers are spatially arranged about the flight deck to provide the correct directionality characteristics. Each sound channel has the appropriate sounds mixed to give realistic content and spread. As with many subjective aspects of simulation, it is sometimes necessary to fine-tune the effects with the help of aircrew who are familiar with the type. The instructor can reduce or mute the sound levels as necessary to facilitate training dialogue.

Simulation of the vibration characteristics is crucial for the training role, and various innovative techniques may be used to create them. The vibrations are closely related to the rotor sounds, but have components at rotor speed, blade-passing speed, and tail-rotor speed plus the possibility of significant harmonics at any of them. The vibration levels vary with pilot control inputs, maneuvers, and aerodynamic conditions; these dynamic characteristics must be identified and used to control the vibration amplitudes.

Since the amplitude and frequency of the vibrations in a rotary-wing aircraft are often of greater magnitude and significance than they are in fixed-wing aircraft, the simulator manufacturer often takes special measures to create them. Simulating these vibrations may take the form of a motion system and a supplementary vibration system. This can be particularly important, for the supplementary system has a higher resonant frequency than the entire simulator platform, enabling it to provide cue information at important frequencies that lie above the main platform resonant frequency. Even with fixed-wing simulators, the motion platform resonant frequency is low enough to prevent the provision of some high-frequency cues.

The simulated flight deck rests on the supplementary vibration system that is itself supported on elastomeric mountings on the main simulator motion system. One or more hydraulic actuators are driven in frequency and amplitude such that the flight-deck floor receives the necessary vibrations while the remainder of the simulator acts as a "ground" and is not vibrated. This provides a more comfortable environment for the instructor, who is located to the aft of the system, and a more satisfactory situation for the visual system and the simulator electronics. The axis of vibration is principally vertical; however, other components can be introduced by the use of separate actuators. The main motion system provides the usual attitude and acceleration cues that complement the vibration cues; the vibration cues may still be used with the main motion system selected off.

The "normal" six-axis synergistic motion system can provide a realistic simulation of many of the attitude and acceleration cues experienced during conventional flight. The major limitation is that any sustained real-world acceleration can only be initiated in the simulator, then "washed-out" to allow the motion system to return to a "neutral"

position so that it can respond with adequate displacement in any direction that the pilot's next input may take it. The sustained attitude characteristics associated with rotary-wing flight can easily be achieved.

The motion-actuator drive positions are computed at high frequency by a transformation of desired platform attitude and position that is itself computed from simulated aircraft attitude and accelerations. The servo control assures that the actuators achieve their commanded positions and thence the motion platform. The motion system activity provides a vital input to the trainee who must use the cues as "man in the loop," just as he does in real life.

Depending on the intended training role, the simulator will probably require a visual system to provide out-of-the-window scenes. The data required for such a system are related to where the training missions are intended to take place. The computer-generated scene requires that a data base of visual objects be created from maps and photographs, and from decisions on what is considered important in the visual scene. The out-of-the-window field of view and cross-cockpit viewing that need to be provided by the visual display are uniquely challenging. From the pilot's eye point, the flight-deck windows of most helicopters provide a wide and deep field of view including a substantial down-looking capability; this can only be properly simulated by a large-mirror multiprojector visual system. It may even necessitate a dome projection visual system. This can have knock-on effects into the size and performance of the motion system supporting the whole simulator.

A major consideration with the visual system is the extent of the field of view that is considered acceptable for training. This has a direct effect on the cost and technical complexity of the visual system and may prevent the adoption of an off-the-shelf display system derived from more traditional fixed-wing simulators.

The accuracy and implementation of the data describing the static and dynamic "feel" forces of the flying controls is critical to the success of the simulator. Because of the tactile nature of the controls, great care must be taken in synthesizing the full range of feel characteristics. The feel synthesis system, often referred to as "control loading," utilizes a stiff mechanical system from the aircraft control stick with its mechanical linkage to an irreversible actuator (often hydraulically powered). In series with the mechanical linkage is a load cell that detects the force that the pilot applies to the stick. By sampling the applied force and computing the expected deflection of the stick from a computer model of the flight-control system, and by then driving the actuator to move the stick, it is possible to re-create the appropriate feel characteristics. The pilot perceives that he is moving the stick against the aircraft feel system; in fact, the actuator is moving

the stick for him in response to the forces he is applying to the flight controls model. In this way it is possible to synthesize all components of the aircraft control feel under full computer control.

Data describing the function and performance of the aircraft systems and avionics are required and must be furnished by the airframe manufacturer and equipment supplier. One method by which the cost of the simulator can be reduced is to simulate as much of the avionics as is possible, rather than use expensive, flight-worthy equipment. For example, the simulator manufacturer can often choose between simulating the autopilot computers and installing real ones. However, the decision as to which option to adopt is not always straightforward. It is necessary to take into account some or all of the following issues:

1. What is the cost of the actual devices relative to the costs of understanding the complexity of and modeling of the functions of the autopilot computer?
2. Are there adequate data to authentically describe the equipment performance in all operating conditions and are they available at reasonable cost?
3. Would the actual devices perform satisfactorily in the simulation environment where the instructor can select freezes and inject step changes in speed, altitude, and geographical location?
4. Can instructor-controlled "faults" be injected to give realistic malfunction scenarios?
5. Can the actual equipment interface requirements be satisfied; that is, power, space, cooling, electrical signals (data buses)?
6. Are the maintenance features adequately described?
7. Is the equipment mature, or if it is simulated, will a series of costly updates be required in order to keep up with in-service development of the equipment?

Recently, the avionics vendors started to reappraise the possibility of providing their software to simulator manufacturers without the aircraft black-box packaging. This could provide a further alternative, if it proves to be cost-effective. This situation has come about because a very high percentage of the cost of a simulator is due to the use of aircraft computers and electronic instrumentation. This means that a high percentage of the manufacturing costs are fixed and out of the control of the manufacturer. From a business perspective this reduces the control over costs, and is very undesirable.

Having reviewed the answers to the above (and possibly other) questions, the manufacturer can make a decision regarding the method to be adopted: "traditional" *simulation* or *stimulation* of "real" aircraft computing equipment. When deciding whether to simulate or stimulate real avionics for fixed-wing devices, it is often necessary to know whether that particular item has been designed to meet the requirements of the ARINC 610 specification. That specification was written to alert the avionics vendors of the need to consider training simulators in their avionics designs. The intention is for the avionics equipment to "know" that it is installed in a simulator and that it is to tolerate certain events that would be considered as sensor failures of one sort or another in a real aircraft. For example, when an instructor selects "Flight freeze" in the simulator, the attitudes and velocities are held constant, but the geographical and altitude integrals are not allowed to accumulate, thereby freezing the aircraft in space. The same must apply to the avionics. They must tolerate this "unreal" situation and be able to fly on when the flight freeze is de-selected. There are a number of other functions covered by the ARINC 610 specification including gross weight change, fuel weight change, and the replay of a previous scenario.

There is clearly a need to develop close and effective working relationships with all the data providers in order to maximize the opportunities for cost-effective simulation that is of appropriate fidelity. For example, experience with fixed-wing training devices has shown that supplementary data may be required at an advanced stage of design or manufacturing in order to address differences in handling qualities perceived by pilots who have significant experience in flying the actual aircraft.

In order for the simulation of the simulated rotary-wing aircraft to navigate and communicate properly, it is necessary to provide a model of its electromagnetic environment with an adequate representation of all applicable radio stations. To achieve this, a regular monthly supply of current data specifying the latitude, longitude, altitude, frequency, and call-sign of each transmitting radio station or beacon is required. Often referred to as ground station data, this information needs to be available on the simulator in its up-to-date form in order to provide a realistic navigational operating environment.

The design method generally used is to adopt a "top-down" approach that analyzes both the operator's stated requirements and the available aircraft data. A picture of the necessary top-level simulator architecture is then developed, which includes all major structural, electronic, motion, visual, simulation, computing, and instructor station components and interfaces.

The simulator manufacturer determines which features already exist in design library form and which will require detailed analysis and design because they are essentially new.

Many of the required simulator features are independent of rotary-wing (or aircraft) type, and these are developed by the manufacturer to suit the required purpose. For example, many simulators require a motion system in order to impart important pitch, roll, yaw, heave, surge, and sway cues to the flight crew in response to maneuvers initiated by the pilot or by simulated weather conditions. On a rotary-wing simulator, the motion system will also be used to provide the vital rotor vibration cues to the crew, cues that are so indicative of performance, maneuvers, and rotor conditions. The motion-system mechanics will probably not need to be developed specifically for the simulator under consideration, since the manufacturer will be able to use a "standard" device whose performance is already established and which can be manufactured with little or no modification to existing designs. The same criteria will apply to components such as the simulator floor frame, the cabin structure, and, to some extent, the electronics that are used to sample flight-deck inputs. Similarly, the main simulator computer and certain software subsystems such as operating systems, atmosphere and weather models, and basic equations of motion may be considered as "standard" elements. This design reuse helps to minimize the costs of developing a simulator and reduces the risk that would be involved in starting from a completely clean sheet each time.

All novel aspects of the design are captured and implemented by using standard techniques wherever possible. Much of this design may involve the software simulation of rotary-wing flight performance together with engine, transmission, and related subsystems.

The design of the performance aspects relating specifically to rotary-wing simulation involves at least the following criteria:

1. *Airframe mass and inertia modeling* as a function of both inherent and instructor-controlled features such as fuel, payload, and center of gravity
2. *Geometric modeling* of fuselage, landing gear, skids, and empennage to enable the generation of accurate body forces and moments caused by aerodynamic forces and ground-contact
3. *Crash-worthiness criteria* such as rotor-to-ground strike conditions, gear collapse forces, rotor overspeed
4. *Aerodynamic force and moment* characteristics in all axes with all relative wind components including main- and tail-rotor-induced effects
5. *Main- and tail-rotor geometry*, characteristics, and control features

6. *Rotor performance model* using either the blade-element or disk method, including all effects of the relative wind, enabling powered flight or autorotation

7. *Rotor torque model* for all conditions including normal powered flight, plus the effects of maneuvers, autorotation, and rotor inertial effects which provide a torque balance with the simulated engine and transmission system

8. *Pitot static system* characteristics as a function of all relative wind components including rotor-induced effects

The designer of rotary-wing simulators has long been faced with a dilemma regarding the choice of rotor modeling technique. Historically, the rotor-disk model has held sway for reasons mainly having to do with the cost of computing. The rotor-disk model is based on an analysis of rotor behavior that considers segments of the blade as finite elements, but then goes on to solve the equations generally as a disk. The disk represents the blade tip-path plane, and the disk pitch and roll angles are the fundamental parameters. It is comparatively economical in its use of computing power and provides an acceptable level of simulation, provided that the boundaries of the flight envelope are not encountered.

If the training mission approaches the flight envelope boundaries and if sufficient real-time computing power is available, then the blade-element model will provide a more authentic flight simulation. The blade-element method is also superior in terms of its dynamic response to pilot inputs. The blade-element model treats each of the blades as having a number of spanwise components (representing equal swept area) and solves the equations of motion of each one in real time at a number of azimuth positions using a relatively high iteration rate. The forces and moments acting on each blade are summed and used to compute an equation of motion for each blade. The resulting flapping- and lagging-blade motion leads to forces and moments that undergo axis transformation before being transmitted into the airframe equations of motion. The process is repeated for each blade. One of the major benefits of this method is its ability to provide a consistent algorithm for predicting rotor vibration and noise.

The blade-element modeling technique has been available for some years now and was thought by some to be a panacea. In reality, it is an improvement over the earlier rotor-disk model, but it does not exhibit absolute authenticity. Some amount of subjective tuning of a range of parameters is still necessary to create the best combination of steady-state and dynamic behaviors.

Irrespective of the method chosen, the modeling of the rotating lifting surfaces associated with rotary-wing vehicles remains a complex process. The aerodynamic forces

in operation are functions of vehicle airspeed and attitude, rotor speed, and blade angles of attack. All of these parameters vary with collective and cyclic control inputs, blade azimuth position, and blade radial position. The resultant non-uniform velocity distribution over the disk is just one source of modeling complexity. Further contributions include the effects of blade flap and lag, introduced either by hinges or through intentional elasticity at the hub. Furthermore, the blades are themselves elastic, and they bend and twist in reaction to the loads that are imposed upon them. In normal flight, the inflow of air is generally down through the rotor. There are, however, areas of reversed flow associated with the "retreating blades." Then there is autorotation during which the inflow is up through the rotor. Add to this the effects of ground-plane proximity and the effect of winds that can come from any direction and it is clear that rotary-wing aerodynamics can never be simple.

The effect of the automatic stability devices installed on many rotary-wing aircraft is to mask the real rotor and airframe behavior. The ability to deselect, or fail, the autostabilizer is of prime importance in a simulator. An accurate portrayal of the raw flying characteristics with the autostabilizer off must therefore be the design aim. The potentially unstable characteristics of this situation add to the simulation engineer's difficulties.

The complexity of the rotor aerodynamics has a direct bearing on the airframe aerodynamics, particularly when combined with the effects of crosswinds and building wakes. The interference effects are notoriously difficult to predict and, because of their nature, are unlikely to be backed up with firm data. The simulation of the tail rotor (when appropriate), usually by means of a disk model, provides another challenge to the designer of the lateral and directional simulation. Suffice it to say that carefully considered inputs from experienced test pilots can provide valuable information for use in the subjective tuning process.

In addition to design data describing "what it is," there is also another type of data that is required in order to validate the performance of the simulator: *how-it-performs* data. These data are generally referred to as *checkout* or *performance* data. They are usually provided by the airframe manufacturer as a set of time-histories representing significant aircraft parameters that have been recorded during the execution of an agreed upon set of specific maneuvers during aircraft flight tests. Ideally, the airframe manufacturer will also provide "proof of match" data that show actual aircraft performance data with his own simulation-model performance overplotted. This gives a clear indication of how close the simulator manufacturer can expect to get to real life performance. The sheet quantity of the data often dictates that they be provided on magnetic media. This enables the simulator manufacturer to process the data digitally, without any likelihood of corruption and with a minimum of effort. Such activity has been common in the fixed-wing simulator arena for many years.

It is the simulator manufacturer's responsibility to provide a training device that matches the performance of the rotorcraft in specific conditions and maneuvers that were recorded during flight tests. The use of judgment in interpreting the match is often necessary. There must be an agreed upon list of appropriate tolerances on the value of each of the flight-test parameters so that a realistic comparison can be made. The prevailing meteorological conditions and a full definition of the initial conditions for each test must be included within the flight-test data parameters that are recorded, since they can strongly influence results.

Checkout data are generally used by the simulator manufacturer for two purposes. First, they are a means of unambiguously confirming the simulated performance to the simulator operator. Second, they may be used in both initial and recurrent tests to confirm to regulatory agencies that the performance of the device is similar and traceable to flight-test results and that the device is therefore suitable for its training purposes. When used in conjunction with an approved training plan, the device may therefore be used instead of an aircraft for obtaining flight crew training credits.

Certain criteria have been established for the measurement of simulation effectiveness. For instance, the simulation industry has developed the term "throughput" to describe any delays associated with the simulation, over and above the corresponding delays that occur in the aircraft. Throughput is an important discriminator, enabling a pragmatic, quantifiable measurement of simulator acceptability to be accomplished for many parameters. Throughput is clearly based on the idea that if a pilot makes an "input" of some sort when flying the real aircraft — perhaps a step input of pitch cyclic stick — then the resultant maneuver can be measured as a time-history showing, typically, pitch cyclic stick position and body pitch acceleration against time. If the same conditions are then set up on the simulator and if the same step input injected, the simulator performs its version of the maneuver and its time-history can be obtained. By choosing identical scales for both aircraft and simulator time-histories, the two can be directly compared, and any delays inherent in the simulator can be measured directly. Provided these delays are only of the order of, say, 0.1 second, the simulator throughput is believed to be acceptable.

It is not only the simulated aircraft pitch acceleration that must come under scrutiny, but also the responses of the motion system, visual system, and instrumentation, together with their integration, if synchronized cue elements are to be provided to the pilot's senses. These tests also need to be conducted in both roll and yaw axes to confirm overall acceptability.

The importance of the flight crew training-instructor/assessor cannot be over-emphasized. Without the instructor, the training device has little or no intrinsic training value. Without the assessor, pilots cannot be certified. In addition to preparing for each

training session, the instructors' functions include controlling and monitoring the training scenario plus timely and effective provision of training, or guidance, to the trainees, as part of the delivery of a structured curriculum. To enable the instructor to perform in his roles efficiently, the simulator manufacturer provides an instructor station, either on board the simulator, close to the trainees, or in some convenient off-board position. The ergonomics of the instructor station and the facilities provided are generally the subject of specific agreements made with the future operators during the design phase of each simulator.

The instructor station typically includes two or more touch-screen and hard-button-controlled visual display units with an instructor-designed interface to the features required to control the training mission. The "look and feel" of the suite of control "pages" is often defined, or influenced, by the users, and may vary in levels of sophistication and automation to suit the envisaged training and checking. Being largely software-controlled, the potential for adaptation is often limited only by one's imagination and the time and cost of specifying and implementing the desired approach. It is at the design stage, however, that functionality is agreed upon, and this is often best achieved by involving future users in demonstrations of previously developed and proved features.

At the beginning of each training activity or check event, the instructor or assessor can select the geographical starting position, knowing that the full set of local navigation and communication radio facilities will be available for the flight. The condition of the pad can also be selected. Initial aircraft conditions, such as fuel load, payload, and center of gravity, can be set up either by using presets or by inserting demanded values. The simulated environmental conditions can be set to suit the planned training/checking activity. Typically, this will include such basic features as temperature, pressure, and lapse rate, all of which can affect vehicle performance. More important, the weather can be selected to produce winds that are either constant or variable. More advanced effects, including precipitation, storms, and even wind shears can be invoked if required.

It is usual for the instructor/assessor to act as air-traffic controller for the purposes of the training session. Although this adds to his workload, it does enable a means of close interaction which would otherwise be missing. Several systems have been developed that provide partial automation of ATC instructions and background chatter. By adapting partial solutions and relying on the instructor to augment the systems, low-cost, credible instructor support can be provided; however, full automation of ATC during scenarios may never be cost-effective.

Certain facilities are often available to the instructor during training. These include (1) *flight-freeze*, which quite literally allows the instructor to stop the training, perhaps to offer advice, then resume it from where it stopped; (2) *reposition*, which en-

ables the instructor to simply select a specific trimmed condition such as short finals from which the pilot may fly on; and (3) *replay*, which enables the instructor to automatically go back over a point of interest or concern from the recent past.

These facilities are of considerable importance during the early phases of flight training, because the instructor can, for example, reset, reposition, and freeze the device to assist the trainee, correct his actions, and reinforce key points. At this stage of training the instructor's role is to be involved in instruction, and these facilities are crucial to enable him to coach the crew. Many of these activities, easily done in the simulator, cannot be accomplished during in-flight training with a rotary-wing aircraft, such as during landing on an oil platform with a high crosswind and low visibility owing to precipitation.

It is at the design stage that the operator chooses the range of the malfunctions that are required to support the planned training; many of these may be related to mandated training and checking events and are referenced to relevant regulatory and airline standards. These malfunctions, which are initiated by the instructor/assessor, can provide realistic effects involving indications, sounds, vibrations, or even smoke in response to a simulated fire. Typically, they are invoked as part of abnormal-procedures training; they can also be used during certification checks as a means of determining the competence of the pilot, generally under flight-critical conditions (such as turbine failure soon after takeoff). Malfunctions may be of a discrete type (such as a generator failure), or of a variable type (such as an oil leak) for which the instructor may choose the rate at which the effect occurs. Malfunctions are an area of the simulation where the provision of reliable, accurate data from which to build the models is crucial, if the introduction of negative training is to be avoided.

It is important that everything possible be done to minimize instructor workload so he can concentrate on the actual training task at hand. For example, lesson plans are often utilized; they are a means of automating the training mission by executing a prepared series of events from preflight initialization through postflight debriefing, including the automatic triggering of malfunctions. In addition, lesson plans are frequently used simply as a means of setting specific flying conditions in order to enable an instructor to rapidly change the status of the simulator in preparation for the next training point. This technique also has the advantage of allowing different instructors to provide a standardized form of training across a range of trainees.

In many ways, the standard of simulation has been governed by the availability of cost-effective technical solutions to simulation problems, the most obvious of these being computing power. Ever since the emergence of digital computers, their computational capabilities have been extended to the utmost in flight simulator applications. The real-time computing demands of flight simulators have always stretched what was avail-

able at reasonable cost, since the computational frequency of the models contributes significantly to their accuracy and throughput, as discussed above.

There have been many phases in computer development relevant to simulation, but it was arguably the adoption of reduced instruction set computing (RISC) and the UNIX operating system that has enabled the greatest strides. A simultaneous increase in power and a reduction in cost have produced a doubling of the iteration rate from 30 Hz to 60 Hz in key simulation areas. The availability of open-systems computing architectures and operating systems has provided platforms that facilitate the development of improved software quality through the availability of a variety of competitive, mature development tools. In addition, the manufacturer is now able to choose from the open market the computing platform best suited to the task, rather than be locked in to a sole-source supplier. This translates into improved simulation models and, hence, better standards of equipment.

Today's flight simulators embody a range of software languages including FORTRAN, C, and Ada. The choice of language is sometimes dictated to the manufacturer, but more often it is based on engineering decisions of language suitability and cost-effectiveness. Perhaps the most important consideration is that the operator should be able to use the delivered computer system, without trepidation, on those occasions when it is necessary to make software modifications. This means that the facilities provided must be simple and safe to use by a simulator maintenance technician. Menu-driven systems and software configuration control are generally provided for this reason.

Extensive efforts are made to support the simulator maintenance technician, whose role is critical in operational support of the equipment once it is installed. The simulator is a complex supersystem involving computer-controlled electrical, electronic, hydraulic, and mechanical systems. Without the diligent support of the maintenance technician, operational performance of the equipment may degrade over time, and preventive maintenance is essential. The task of maintenance requires skills in all of the usually mutually exclusive domains of the systems just mentioned, and requires extensive training and support by the manufacturer.

This maintenance requirement manifests itself in the design of the equipment: it is made to allow maintenance tasks to be carried out as conveniently as possible, especially bearing in mind that the expected life of the device may be as long as 20 years. During that period many of its systems will become partly or completely obsolete, and significant updates may take place. Which is to say that when a simulator is installed, the manufacturer is entering into a lifelong support commitment, which has very significant logistical implications for the manufacturer. For instance, a customer-support operation has to be available and must be able to respond rapidly to diverse areas of the world in

order to attend to equipment built up to 20 years ago. In addition, the cost burden of a spares inventory and storage space, both centralized and at outstations, has to be considered.

At the conclusion of the manufacturing phase of the training device an important milestone must be achieved: simulator acceptance and approval. It is the point at which the simulator is offered to the buyer for testing purposes in order to confirm that it meets its specifications and that it is suitable for use as a training device; clearly this is an important contractual commitment. This is generally interpreted as meaning that the simulator behaves like the aircraft it simulates, and that it meets the instructor's need for control of the training mission.

During the first phase — simulator acceptance — the simulator is subjected to a large number of tests that provide documentary evidence that the simulator and all its subsystems meet their design criteria. The actual tests are written by the simulator manufacturer and approved by the buyer many weeks before the final acceptance phase. The tests demonstrate that for a given set of initial conditions, flight-deck inputs will produce specific outputs. Satisfying the tests means that the simulator and its subsystems perform as expected according to the design data. In some instances, this conformance with design data may not meet with the user's expectations. In such circumstances, and by mutual agreement, the performance and the test criteria may be adjusted away from the original design standard. There may be some instances when there are no objective standards, in which case the user is requested to assist the manufacturer in meeting expectations by subjectively tuning the performance until an agreement is achieved. Motion cues are an area in which this may be successfully achieved.

The second phase is that of regulatory body approval. Each country has its own aviation simulation equipment regulators. For the United States, the FAA has been diligent in working with the aviation industry to secure an efficient and effective standards plan for fixed-wing devices that has been emulated worldwide. A standard for use in the rotary-wing world is now in the final stages of preparation for issue and use: FAA Advisory Circular 120-63. It provides a means whereby an operator may submit a training device for approval at a particular level under the FAA's Advanced Simulation Plan. During the approval, the regulatory body representative will witness the tests and verify whether the simulator meets the necessary standard. Each of the "flying" tests will be run manually, as well as in an automatic mode, to ensure that the necessary consistency exists. It is important to realize that these tests concern equipment functions and standards of performance. They do *not* imply that flight crews will be able to perform adequately in their workplaces — this outcome is dependent on the application of training regulations and standards as embodied in a curriculum and facilitated by expert instructors, using the simulator as a *training tool*.

The tests will have been set up by the simulator manufacturer to verify that the simulator performance matches that of the aircraft under similar conditions. The tests are documented in an Approval Test Guide (ATG). The results are compared with flight-test data from the aircraft by using overplotted time-histories. Appropriate tests are conducted on each of the flying controls to establish the authenticity of static forces and dynamic responses. Throughput tests are conducted on the instrumentation and on the motion and visual systems to determine if throughput is acceptable. Objective tests of the sound and vibration systems are undertaken, and an analysis conducted to demonstrate compliance with flight-test data. If the initial evaluation is successful, the simulator is awarded the appropriate level of approval. Recurrent evaluations using the original ATG are necessary each year for the lifetime of the equipment to ensure that the performance of the simulator remains consistent with the same standard demonstrated in the initial evaluation.

Tomorrow

In the field of rotary-wing training, it will be helpful if the simulator manufacturer can be more responsive to the operator's circumstances and needs. In many cases, operators do not need the capability of a large and expensive flight simulator, either because of operational constraints or because their fleet of aircraft is small or diverse. Such situations might encourage the development of portable simulators that could be hired by operators for relatively short periods to perform a particular training task and then returned to some central pool.

Presently, equipment is designed to be permanently sited, a logical outcome of the combination of acceleration requirements and the mass of the platform. Portability requires either (1) that the dynamics of the environment be modified to allow the mounting of the motion system (whatever that may need to become) on a platform such as an articulated trailer capable of being moved on the highways, or (2) a significant development in the design of the various simulator "modules" to enable rapid top-level assembly and dismantling, with minimal testing and adjustment subsequently required to enable simple and rapid re-certification before being used for training. Advances in computing and input/output linkage will enable these areas to be adequately "miniaturized" and "ruggedized." It is clear from the above that portability requires that major philosophical and pragmatic issues be overcome; consequently, it will require not only significant investment to provide, but also a cultural shift in the entire vendor structure, from the sales process through to design, manufacture, and installation.

As an alternative, locating equipment at the "point of demand" is a well-tried technique, particularly in the case of smaller, lower-cost, fixed-wing aircraft in a training center kind of environment where training time, wet or dry, is sold to operators. As men-

tioned earlier, the main global regions expected to sustain rotary-wing market growth are in the Third World, and the economic and demographic character of these regions is changing rapidly. Locating training centers in these regions equates to both the opportunity for significant business and high risk. This is especially likely, for the effect of AC 120-63 will be relatively delayed in these regions because of their development and the extremely high rate of economic growth that will be required to sustain expected purchases.

Another possibility might be to provide a massively re-configurable training device that could be adapted, within a short time, to meet a particular operator's various needs; the enormous range of available helicopter variants would encourage this approach. Such a device would be expensive to build, requiring very high availability and utilization in order to cover its depreciation costs alone — depreciation costs associated with highly specified fixed-wing simulators are presently of enormous concern to their owners and operators.

It is in the above areas that the radical reappraisal of approach to the design, manufacture, and support of rotary-wing trainers is most likely to bear fruit.

In order to provide better training devices in the future, it will be necessary for the airframe and simulator manufacturers to work together to come up with better models for describing rotor performance. These models, which will inevitably require more computing power, may have to include effects describing rotor-blade elasticity, which are currently ignored or simplified. The use of a simplified blade-element model for the tail rotor may be necessary to enhance the lateral and directional handling characteristics. It may also be possible for data-gathering investigations to be planned, involving flight-test pilots and experienced rotary-wing aerodynamicists, that could either provide more realistic models than are currently available or that could advance our knowledge of the terms that are best tuned subjectively. Ideally, this activity should concentrate on the autostabilizer-off characteristics, which are easily enhanced by the autostabilization simulation. Inevitably, these investigations will initially have to be type-specific and presumably aimed at specific simulator contracts. They would, however, contribute to an expanded, general level of understanding that would benefit all parties in the long term.

Because of the near-ground operations that characterize many rotary-wing missions, a better appreciation must be obtained of the rotor interference effects that are caused both by the ground and by crosswinds. This should directly translate into better training for takeoff, hover in ground effect, and landings, maneuvers that occur so frequently.

With the advent of Advisory Circular AC 120-63, the airframe manufacturers will need to provide data at least to the same standards and extents they do for fixed-wing

aircraft training equipment. Thus far they have not needed to do this for approval purposes.

There are, of course, several configurations other than that of the classic helicopter to consider. Relatively few simulators have been built in the past for tandem rotor, coaxially counterrotating, or even no-tail-rotor aircraft. The simulation of tilt-wing and tilt-rotor aircraft, which are likely candidates for mass production in the future, will be complicated because of their reconfigurability. The propulsion and transmission systems in these aircraft will require careful analysis and modeling in order to provide realistic training.

Quite understandably, the developers of tomorrow's flight training equipment will, wherever appropriate, attempt to achieve fidelity that is better than that available in today's devices, purely as a part of the competitive battle to provide discriminators that improve the likelihood of purchase. However, as the emphasis shifts toward more technologically developed flight decks, the training equipment will have to reflect the requirements of the changing role of the flight crew, and their necessary training. Since this discussion is focused on the manufacturing of training devices, it has not seemed appropriate to consider the fundamental changes in training that have to occur, and that indeed have started to occur, in the aviation industry in response to the training needs for modern aircraft.

However, as has recently been strongly recommended following accidents involving high-technology fixed-wing aircraft, the changing role of the flight crew is not simply an issue for improved human factors training — it is an issue for the entire approach to the business of selecting, conditioning, and maintaining crew proficiency. The "stick and rudder" legacy flight crew members who have transitioned to a second-generation glass environment require training that is significantly different from that they have become accustomed to. The authors strongly believe that the manufacturers of training equipment have a responsibility to tackle the new training problems in a proactive fashion, rather than wait for human factors initiatives from trainers and industry consultants to become mandated (perhaps in not the best way) and then react to them. As such, we maintain a close involvement in discussions contributing to the proposed revisions of the LOFT and cockpit resource management (CRM) Advisory Circulars, and are actively involved in the AQP process that is developing at several North American operators — changing our equipment in response to changes in training needs.

In practice, as a manufacturer the situation is far from ideal, because of the momentum associated with conventional simulation equipment standards. However, it is clear that changes in fixed-wing cockpit technologies and the character of the demands that they place on flight crews will also occur with rotary-wing aircraft.

One outcome of training processes associated with advanced aircraft is the increasing use of part-task and classroom trainers. The fixed-base or vibration-base approach makes it possible to reduce the cost of the simulator by providing a simulator without a motion platform or even an out-of-the-window visual scene. This type of device facilitates procedural training and systems familiarization, including "free-play," to enable the trainee to fully understand the operation of each particular system and, more important, the interactions between systems. There would also be the capability to provide limited rotor-induced vibration cues (at lower cost than using a full motion system) by introducing a vibration generator into the floor frame or seat mountings.

The use of simulation offshoots in the classroom may also be considered advantageous to the overall training scheme. Computer-based training for helicopters has established an initial footing in this area, with various training modules being available on a personal computer, thus enabling self-paced or instructor-led training. This kind of approach has become ubiquitous among commercial and military fixed-wing operators during the last 6 years. Computer power has also increased to such a point that it is now routine to present, for example, "virtual" instruments on the computer screen sourced from the main simulator computer. Here, in a highly graphical environment, it is possible for training subject matter to be introduced to a group of trainees, and then for each trainee to proceed to exploit the training features at his own rate and to whatever extent necessary in a structural way. The trainee will have the benefit of system operation in real time with the same responses as those he would experience in the simulator, with the same software version of helicopter configuration. Again, graphical representations are often considerably less expensive than "the real thing," hence, training costs can be minimized. This kind of technology is now becoming independent of the main simulation computation engine, with highly realistic, fully independent systems and aircraft models becoming available at low cost as personal computers.

A training package must be focused on the kinds of training to be performed — initial, recurrent, transition to new aircraft type, upgrade to pilot, or any other form of training.

Simulator training may also be required for airframe and avionics maintenance personnel who will increasingly gain access to BITE (built-in test equipment) data via the flight-deck equipment. Here, the particular strength of the simulator comes into its own. It is possible to introduce a range of "faults" that require systematic interrogation of on-board equipment that would never be practical to set up or achieve on a line aircraft. The trainees will be able to fault-find and practice the replacement of apparently failed LRUs

(line replaceable units) without any risk of damaging the simulator hardware, themselves, or anyone else. An instructor can always be on-hand to provide training inputs, to offer advice, and to help the trainees to find the solution themselves. This kind of training can have a direct effect on inventory and time-to-repair, which are especially important in operations when a rapid turnaround of the aircraft is required and when delays cause revenue losses and even flight cancellations.

CONCLUSIONS

In flight training, the manufacturers of the training devices are often playing a game of catch-up with the airframe and avionics manufacturers. Aviation technology will never stand still; therefore, the need to train and retrain operators will never go away so long as technology is insufficiently advanced and customer confidence is insufficient to lead to a replacement of the "man in the loop." As regulatory bodies around the world agree on procedures for the use of rotary-wing flight training equipment, the importance of these devices is likely to be maintained.

It is almost certain that a wide range of training devices will be necessary to meet the many and varied needs of the operators. On the basis of their success with fixed-wing training devices, the simulator manufacturers are well placed to meet these needs, but they must adapt to the fact that the operational environment and business conditions of rotary-wing operations are rather different from those of the commercial fixed-wing operators.

The need for high-fidelity training equipment relates in particular to maneuvers performed close to the ground. Improvements can be made in this area, however, only through a necessary and measurable increase in the quality and accuracy of the data available for the simulation design process in order to take advantage of increases in the computation power that is becoming available at lower and lower cost. Improvements will undoubtedly be partly facilitated by a closer and more harmonious working relationship to be established between the four main parties — the training equipment user, the equipment manufacturer, the airframe manufacturer, and the regulator — to ensure that the training equipment design closely matches customer needs.

The result will be seen as training systems that are more adaptable and acceptable than any we have today. Following the recent publication of AC 120-63, the role of the FAA's Advanced Simulation Plan in the rotary-wing arena may potentially have as strong an effect on the training aspirations of the operators as it did for the fixed-wing community. We all hope that it leads to increased safety and profitability in the complex but highly stimulating world of vertical flight.

8 SIMULATOR AERO MODEL IMPLEMENTATION

Thomas S. Alderete*

SUMMARY

A general discussion of the type of mathematical model used in a real-time flight simulation is presented. It is recommended that the approach to the development of a mathematical model include modularity and standardization, for modification and maintenance of the model will be much more efficient with this approach. The general equations of motion for an aircraft are developed in a form best suited to real-time simulation. Models for a few helicopter subsystems are discussed in terms of general approaches that are commonly taken in today's simulations.

INTRODUCTION

The purpose of this chapter is to provide the reader with an understanding of the type of mathematical model used in a real-time flight simulation. A flight simulation system is studied in order to gain a better understanding of the real (or planned) aircraft. The understanding or knowledge to be gained can relate to a wide variety of subjects, including engineering studies, handling qualities, or pilot training. To properly perform a simulation we need a total system, including a mathematical model, simulator hardware, a visual system, and a motion system, whose behavior is sufficiently similar to that of the aircraft in the subject areas under investigation. The mathematical model is a key part of this total simulation system.

Before delving into some of the technical aspects, it is important to examine what is meant by the phrase "mathematical model," or more simply, "math model." Is it the equations and data that describe the aircraft's behavior? Is it the computer program and all the associated data used to compute where the aircraft is and what it is doing? Does it include "fudge factors" used to "tune-up" the simulation's performance? What about all the integration algorithms and numerical "tricks" used to improve the solution; are they part of the math model? Naturally, there are different opinions as to what the math model includes; the following provides a definition useful to the present discussion:

The mathematical model is the description and specification of the aircraft's dynamic behavior. This behavior comprises the various motions of the airframe and the states and performances of the various subsystems, such as the engine, landing gear, and avionics. The math model considers all the external and internal influences on the aircraft and defines the resultant states of the aircraft and its subsystems.

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The model is best presented by mathematical equations, schematic diagrams, logic diagrams, tables, and graphs of data including geometry, aerodynamic coefficients, and gain schedules. These engineering equations, diagrams, and data comprise the mathematical model.

The digital computer program, and its associated data, constitutes an implementation of the mathematical model. It is not the model itself, but rather a method (non-unique) of computing the model. The answers obtained by means of these calculations are used to validate the mathematical model. The basic idea of validation (covered in Chapter 9) is twofold: (1) to verify whether the program accurately solves the equations of the model, and (2) to validate that the model accurately describes (predicts) the behavior of the aircraft.

This discussion of simulation mathematical modeling will describe the general elements of a model. The complete model can be thought of in two parts, the general equations of motion and the specific aircraft subsystems. The general equations of motion for a rigid body will be derived; however, because these equations and their derivation are well known, not all details will be given here. Emphasis will be on a particular form of the general equations that is best suited to real-time simulation. Modeling methods for various subsystems such as the aerodynamics, engine, control systems, and so forth will be discussed in much less detail, without derivation or specific model examples. The subsystems are, of course, specific to a given aircraft design and configuration. Some general approaches used in today's simulations are also discussed. A list of symbols appears at the end of the chapter.

MODEL STRUCTURE

The common and highly recommended approach to the development of mathematical models is to employ the principles of modularity and standardization. Later, when the computer program implementation of the math model is designed, these principles will provide a significant pay-off in efficiency and maintainability. A modular approach requires that the model be broken down into smaller parts that share information and interact in clear and meaningful ways. The modules usually follow along lines that correspond to the physical components of the aircraft (the program design may not). Standardization of axis systems, nomenclature, and various mathematical and engineering conventions also provides significant benefits both in the programming implementation and in communicating the meaning of the model to others. These principles have great economic benefit if more than one type or model of aircraft is to be simulated. Modules can be updated or replaced without rewriting the complete program. Also, standardization allows modules to be shared between different simulations.

With a modular approach to math modeling, it becomes necessary to define information interfaces. What does each module need for input? What does it provide as output to other modules? In some cases, an output requirement is defined by some other module. For instance, the rotor module might not actually need to compute "horsepower required" in order to model all the rotor states, but a transmission module might require it. Some modules will require inputs from or will provide outputs to the "outside world," that is, external to any modeling. Pilot controls are an

example of an external input, and pilot station accelerations might be an example of an output needed for a motion-generation system, but not by the model itself.

A typical model organization is depicted in figure 1. Each bubble indicates a particular module and the lines and arrows indicate information flow. Certainly there will be numerous other modules and other information paths as dictated by the actual aircraft's subsystems. Also, it would be common for nearly all the modules to have access to the environmental parameters and to the aircraft's state variables.

The modular breakdown of the math model shown in figure 1 suggests a major design approach and some guidelines for standardization. The modules to the left of the central summation bubble all are specific to a particular aircraft. The summation, equations of motion, and environment modules are general to all aircraft and can form the standard, or "core," modules for any simulation. The specific description of a particular aircraft should include the aerodynamic, propulsion, and landing gear forces and moments acting on the aircraft center of gravity. The standard modules sum the reactions and produce aircraft state variables (as well as numerous ancillary computations).

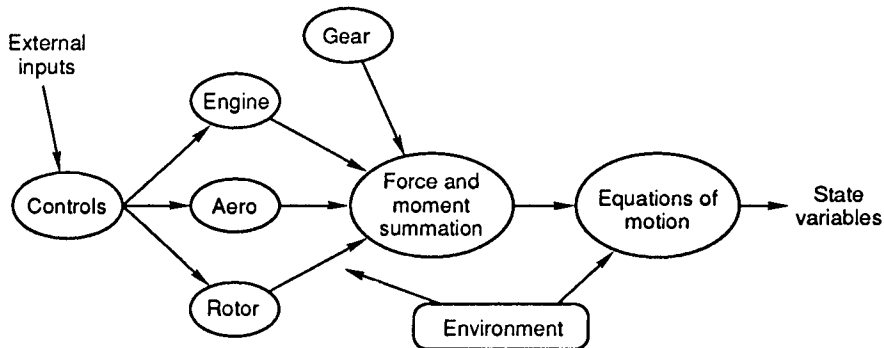


Figure 1. Typical model organization.

The mathematical model will be examined in two steps. First, the general equations of motion that form the core of the simulation will be developed. All the equations necessary to predict the aircraft's state when the external forces and moments are known will be derived. A standard text on dynamics should provide any details omitted in this treatment (cf. refs. 1, 2). Next, some of the typical aircraft-specific modules will be examined. The equations for these modules will not be derived or presented in any detail; a general discussion will suffice to give the reader some idea of what might be included in an actual model.

GENERAL EQUATIONS OF MOTION

An aircraft in flight has six degrees of freedom, three translational and three rotational. If the equations of motion are written relative to the aircraft's center of mass, the translational and rotational sets of equations are independent of each other

and can be derived separately. For this derivation, a nonrotating Earth will be assumed, which simplifies the understanding of the equations. If required, the effects of Earth's rotation can be added to the general equations at a later time without much difficulty. Neither are wind and turbulence considered in the derivation that follows. Guidance on how air disturbances may be added is given later on.

Axis Systems

Before beginning the derivation, the various axis systems that are commonly used in flight simulation will be discussed. The body-, local-, and inertial-axis systems are germane to the equations of motion; they are discussed below. Other axis systems will be mentioned when some of the aircraft subsystems are discussed.

The equations of motion are written with respect to the body-axis system. Referring to figure 2, the body axis has its origin at the aircraft center of gravity, c.g. The x-axis is pointed forward out the nose; the y-axis is pointed out the right side of the aircraft, and the z-axis is directed down through the underside of the aircraft. The body axis is fixed to the aircraft and moves along with it. It forms a right-handed triad.

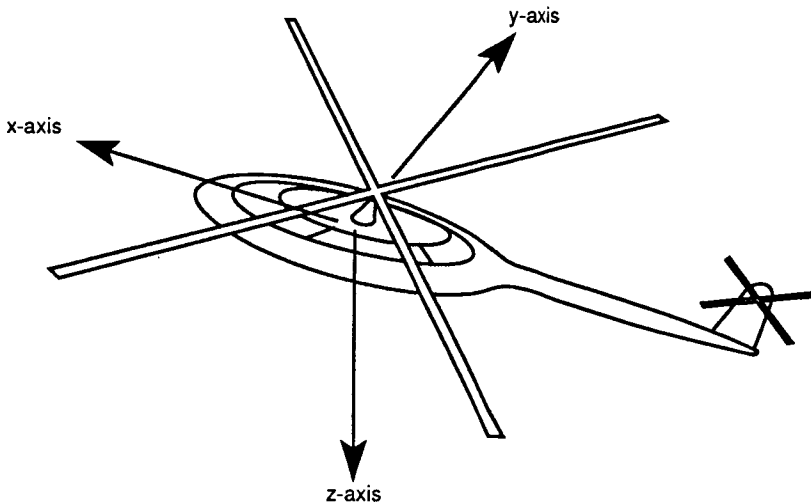


Figure 2. Body-axis system.

The local axis system also has its origin at the aircraft's c.g., but has a fixed orientation. The X_L -axis always points north, the Y_L -axis points east, and the Z_L -axis points down. The local frame is depicted in figure 3.

For purposes of this discussion, an inertial frame (X_E , Y_E , Z_E) is taken as one that has its origin fixed at some point on Earth's surface. (For a rotating Earth, placing the origin at Earth's center would be a better choice.) Its fixed orientation is the same as the local frame and is also depicted in figure 3.

Turning attention once again to the body-axis system, some other definitions and relationships can be developed. Whenever the x , y , or z axes are referred to without any subscripts, the body axis is implied. The six body-axis velocities are shown in figure 3. The terms u , v , and w are the body-axis translational velocities in the x , y , and z directions, respectively. The terms p , q , and r are the body-axis rotational velocities about the x , y , and z axes, respectively.

The aircraft orientation is described by an ordered set of three Euler angles, ψ , θ , and ϕ , that relate the orientation of the body axis relative to the local axis system. In figure 4, the axis system designated by X_1 , Y_1 , and Z_1 is the initial reference orientation (in this work, it corresponds to the local frame). First, the aircraft is given a rotation ψ about the Z_1 axis in the sense shown in the figure. This aligns the body axis with the system labeled X_2 , Y_2 , and Z_2 . Next, the aircraft is rotated by θ about the Y_2 axis. The result is now the X_3 , Y_3 , and Z_3 frame. Finally, the aircraft is rotated by ϕ about the X_3 axis, yielding the X , Y , Z frame, the final orientation of the body-axis system.

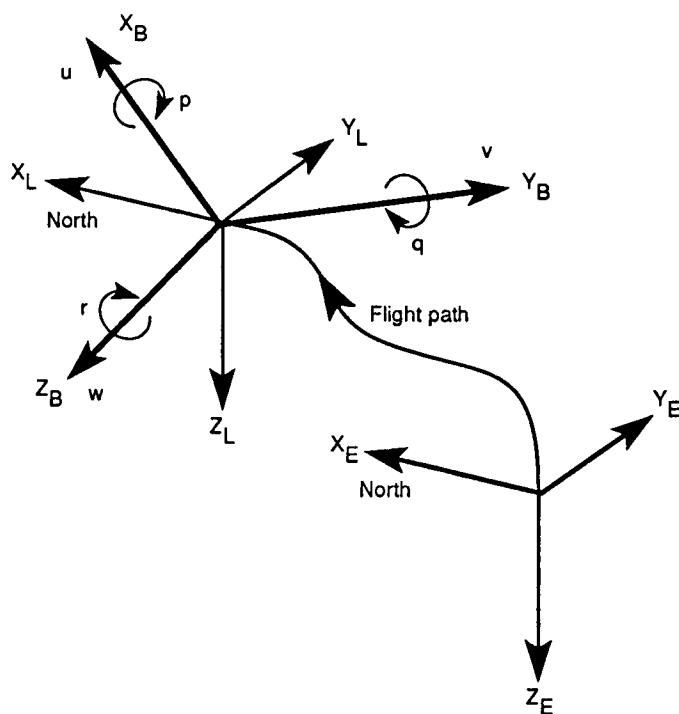


Figure 3. Inertial (E), local (L), and body (B) axes.

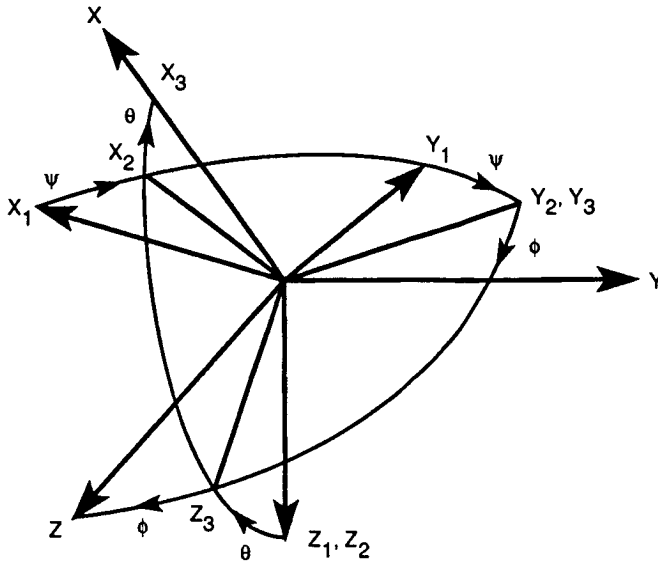


Figure 4. Aircraft orientation using Euler angles.

A pair of useful transformation matrices are those that rotate a vector from the local- to the body-axis system and from the body- to the local-axis system. Referring again to figure 4, the following three equations can be written.

The first rotation ψ results in

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Next, the rotation θ results in

$$\begin{bmatrix} X_3 \\ Y_3 \\ Z_3 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix}$$

And finally, the rotation ϕ yields

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} X_3 \\ Y_3 \\ Z_3 \end{bmatrix}$$

Combining the three matrix multiplications into one, results in

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ -\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi & \cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi & \cos\theta\sin\phi \\ \sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi & -\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi & \cos\theta\cos\phi \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

This transformation matrix will be referred to as [LtoB] (read "local to body"); the above equation can then be written as

$$\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = [\text{LtoB}] \begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix}$$

Also, since the transformation matrix is orthogonal, the inverse matrix can be obtained by a simple transpose. Therefore,

$$[\text{BtoL}] = [\text{LtoB}]^{-1} = [\text{LtoB}]^T$$

and

$$\begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} = [\text{BtoL}] \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

Translational Equations

The equations of motion are developed in the body-axis system because the external forces are most easily defined in a coordinate system fixed in the aircraft. If \bar{F} is the total external force acting on the aircraft, \bar{v} is the absolute velocity of the center of mass, and if m is the aircraft mass, then the following can be written:

$$\bar{F} = m\dot{\bar{v}}$$

The \bar{F} and \bar{v} vectors may be written in terms of their x , y , and z components:

$$\begin{aligned} \bar{F} &= F_x \hat{i} + F_y \hat{j} + F_z \hat{k} \\ \bar{v} &= u \hat{i} + v \hat{j} + w \hat{k} \end{aligned}$$

where \hat{i} , \hat{j} , and \hat{k} are an orthogonal triad of unit vectors aligned with the x , y , and z body axes, respectively. If the aircraft (and the body-axis frame) is rotating with angular velocity $\bar{\omega}$, then the absolute acceleration can be found as follows:

$$\dot{\bar{\mathbf{v}}} = (\dot{\bar{\mathbf{v}}})_r + \bar{\boldsymbol{\omega}} \times \bar{\mathbf{v}}$$

where $(\dot{\bar{\mathbf{v}}})_r$ is the acceleration as viewed from the body-axis system and the " \times " symbol signifies a vector cross-product. This expression for the rate of change of a vector in a rotating system will be used repeatedly in the following derivations. The relative acceleration can be expanded as

$$(\dot{\bar{\mathbf{v}}})_r = \dot{u}\hat{\mathbf{i}} + \dot{v}\hat{\mathbf{j}} + \dot{w}\hat{\mathbf{k}}$$

Also, the rotational velocity vector can be written as

$$\bar{\boldsymbol{\omega}} = p\hat{\mathbf{i}} + q\hat{\mathbf{j}} + r\hat{\mathbf{k}}$$

Now the cross-product can be evaluated and written as follows:

$$\bar{\boldsymbol{\omega}} \times \bar{\mathbf{v}} = (wq - vr)\hat{\mathbf{i}} + (ur - wp)\hat{\mathbf{j}} + (vp - uq)\hat{\mathbf{k}}$$

Gathering terms and writing the vector equation in terms of three scalar relationships, we have

$$F_x = m(\dot{u} + wq - vr)$$

$$F_y = m(\dot{v} + ur - wp)$$

$$F_z = m(\dot{w} + vp - uq)$$

Note that in some formulations the gravitational force terms are explicitly written at this juncture. They are not included here for reasons to be made clear later. However, for illustration, the three force components could be written as follows:

$$F_x = F_{x \text{ Applied}} - mg \sin\theta$$

$$F_y = F_{y \text{ Applied}} + mg \cos\theta \sin\phi$$

$$F_z = F_{z \text{ Applied}} + mg \cos\theta \cos\phi$$

Rotational Equations

If $\bar{\mathbf{M}}$ is the total external moment acting at the center of mass and $\bar{\mathbf{H}}$ is the angular momentum, then the following can be stated:

$$\bar{\mathbf{M}} = \dot{\bar{\mathbf{H}}}$$

The applied moment \bar{M} can be written as

$$\bar{M} = L\hat{i} + M\hat{j} + N\hat{k}$$

The first task is to write an expression for the angular momentum, and then to find its rate of change with respect to time. The angular momentum of a rigid body about its center of mass is given by

$$\bar{H} = \sum_i \bar{R}_i \times m_i \dot{\bar{R}}_i$$

where \bar{R} is the position vector of a particle m_i . Assuming that the position of each particle is fixed in the body, then the velocity of each particle is simply

$$\dot{\bar{R}}_i = \bar{\omega} \times \bar{R}_i$$

where $\bar{\omega}$ is the absolute angular velocity of the body. Further assuming that the body has a continuous mass distribution, the particle mass can be represented by its density times an elemental volume, ρdV (ρ is mass density). Substituting the expressions for velocity and elemental volume, the summation can be replaced by an integral:

$$\bar{H} = \int_V \rho \bar{R} \times (\bar{\omega} \times \bar{R}) dV$$

Let $\bar{R} = x\hat{i} + y\hat{j} + z\hat{k}$ for a given elemental volume and, as previously $\bar{\omega} = p\hat{i} + q\hat{j} + r\hat{k}$. The vector cross-products can be written as

$$\begin{aligned} \bar{R} \times (\bar{\omega} \times \bar{R}) &= [(y^2 + z^2)p - xyq - xzr]\hat{i} \\ &\quad + [-yxp + (x^2 + z^2)q - yzr]\hat{j} \\ &\quad + [-zxp - zyq + (x^2 + y^2)r]\hat{k} \end{aligned}$$

Now, the moments and products of inertia can be defined as

$$I_{xx} = \int_V \rho(y^2 + z^2) dV$$

$$I_{yy} = \int_V \rho(x^2 + z^2) dV$$

$$I_{zz} = \int_V \rho(x^2 + y^2) dV$$

$$I_{xy} = I_{yx} = \int_V \rho xy dV$$

$$I_{xz} = I_{zx} = \int_V \rho xz dV$$

$$I_{yz} = I_{zy} = \int_V \rho yz dV$$

Substituting these definitions, plus the cross-product terms, gives the angular momentum as

$$\begin{aligned} \bar{H} = & (I_{xx}p - I_{xy}q - I_{xz}r)\hat{i} \\ & + (-I_{yx}p + I_{yy}q - I_{yz}r)\hat{j} \\ & + (-I_{zx}p - I_{zy}q + I_{zz}r)\hat{k} \end{aligned}$$

For the typical aircraft case of symmetry with respect to the xz -plane,

$$I_{xy} = I_{yx} = I_{yz} = I_{zy} = 0$$

Simplifying the expression for angular momentum, we have

$$\bar{H} = (I_{xx}p - I_{xz}r)\hat{i} + (I_{yy}q)\hat{j} + (-I_{xz}p + I_{zz}r)\hat{k}$$

Now, turning attention back to the rotational equation of motion, the time rate of change of angular momentum can be written as

$$\begin{aligned} \bar{M} &= \dot{\bar{H}} \\ &= (\dot{\bar{H}})_I + \bar{\omega} \times \bar{H} \end{aligned}$$

where $(\dot{\bar{H}})_r$ is the rate of change of angular momentum observed from the body-axis system (rotating system). Expanding terms gives

$$(\dot{\bar{H}})_r = (I_{xx}\dot{p} - I_{xz}\dot{r})\hat{i} + I_{yy}\dot{q}\hat{j} + (-I_{xz}\dot{p} + I_{zz}\dot{r})\hat{k}$$

and

$$\begin{aligned}\bar{\omega} \times \bar{H} &= (\bar{H}_z q - H_y r)\hat{i} + (H_x r - H_z p)\hat{j} + (H_y p - H_x q)\hat{k} \\ &= [(-I_{xz}p + I_{zz}r)q - (I_{yy}q)r]\hat{i} \\ &\quad + [(I_{xx}p - I_{xz}r)r - (-I_{xz}p + I_{zz}r)p]\hat{j} \\ &\quad + [(I_{yy}q)p - (I_{xx}p - I_{xz}r)q]\hat{k}\end{aligned}$$

Collecting terms and writing in terms of three scalar equations:

$$L = I_{xx}\dot{p} - I_{xz}\dot{r} - I_{xz}pq + (I_{zz} - I_{yy})qr$$

$$M = I_{yy}\dot{q} + (I_{xx} - I_{zz})pr + I_{xz}(p^2 - r^2)$$

$$N = I_{zz}\dot{r} - I_{xz}\dot{p} + (I_{yy} - I_{xx})pq + I_{xz}rq$$

The above three equations, plus the three translational equations comprise the equations of motion for the rigid-body aircraft. However, a number of problems arise if these equations are used to compute the aircraft's dynamic state for simulation purposes.

One problem with the translational equations is that the body axis is moving along the flight path and so the position of the aircraft relative to some fixed point (like a runway) is not easily specified. Another problem or "undesirable" feature is the presence of the various products involving rotational velocity terms, such as (wq) and (vr) . These terms could cause problems with numerical accuracy when rotational velocities have large magnitude or frequency content. This situation is remedied by a transformation to an inertial frame, located on Earth's surface.

For the rotational equations, there is the problem of the equations being coupled via \dot{p} , \dot{q} , and \dot{r} , which can lead to complications during numerical integration. To resolve this problem, the three equations can easily be decoupled by algebraic manipulation. Another issue concerns the aircraft orientation, which cannot be found

Transformation of Translational Equations to an Inertial Frame

For the flat, nonrotating Earth considered here, any fixed frame of reference can be employed as an inertial frame. The three forces acting on the aircraft center of gravity in the body-axis system are rotated back through the Euler angles to the local frame and translated back to some convenient origin.

Again, the rotation from body axes to the local frame is given by

$$\begin{bmatrix} F_N \\ F_E \\ F_D \end{bmatrix} = [BtoL] \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}$$

where once again the subscripts N, E, and D designate the north-, east-, and down-pointing directions. The accelerations are then

$$\begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix} = \begin{bmatrix} F_N/m \\ F_E/m \\ F_D/m \end{bmatrix}$$

A note can be made here about computer program implementation. If the body-axis forces are taken so as to *not* include the gravitational terms, then the aircraft's weight can be added into the above equation as follows:

$$\begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix} = \begin{bmatrix} F_N/m \\ F_E/m \\ (F_D + \text{weight})/m \end{bmatrix}$$

This implementation avoids the necessity of rotating the gravitational terms twice. That is, instead of projecting the aircraft weight into the body-axis frame and then rotating the summed forces into the inertial frame, the above suggestion allows the weight to be summed directly into the "down" force component in the inertial frame.

The accelerations can then be integrated to get velocities in the local frame and can be integrated again for displacements. The displacements can be referenced to any convenient location such as a runway threshold, navigation waypoint, or whatever is most useful to a simulation. The set of translational equations previously

defined in the body-axis system will prove useful for computing body-axis accelerations at a later time.

Modifications to the Rotational Equations

The equations for L, M, and N are manipulated to yield \dot{p} , \dot{q} , and \dot{r} on the left-hand side:

$$\dot{p} = \frac{I_{zz}}{D} L - \frac{I_{xz}}{D} N + \left[\frac{(I_{xx} - I_{yy} + I_{zz}) I_{xz}}{D} \right] pq + \left[\frac{(I_{yy} - I_{zz}) I_{zz} - I_{xz}^2}{D} \right] rq$$

$$\dot{q} = \frac{1}{I_{yy}} M + \frac{(I_{zz} - I_{xx})}{I_{yy}} pr + \frac{I_{xz}}{I_{yy}} (r^2 - p^2)$$

$$\dot{r} = -\frac{I_{xz}}{D} L + \frac{I_{xx}}{D} N + \left[\frac{(I_{xx} - I_{yy}) I_{xx} + I_{xz}^2}{D} \right] pq + \left[\frac{(I_{yy} - I_{xx} - I_{zz}) I_{xz}}{D} \right] rq$$

where D is defined as

$$D = I_{xx} I_{zz} - I_{xz}^2$$

These uncoupled equations can now be integrated with respect to time to obtain p, q, and r. The resultant rotational velocities cannot be integrated to get angular displacements; that is, one cannot find a set of three parameters that define the aircraft's orientation and that have p, q, and r as their time-derivatives. In some formulations, direction cosines are used to describe the angular orientation; this involves nine direction cosines and six equations of constraint. One can also use various four-parameter systems, so called quaternions. Quaternions have the advantage of not having singularities (gimbal lock), of having one half the frequency content, and of involving one equation of constraint. Aircraft orientation can also be specified by the use of Euler angles. Remember that Euler angles are an ordered set of three parameters and that there will be a singularity when the aircraft is pointed straight up or down.

What is needed is a relationship between time rates of change of the Euler angles and the body-axis rotational rates. Assume that $\dot{\phi}$, $\dot{\theta}$ and $\dot{\psi}$ are the angular velocity *vectors* associated with rates of change in the corresponding Euler angles. Then the total rotational rate vector can be written as

$$\bar{\omega} = \dot{\psi} + \dot{\theta} + \dot{\phi}$$

Note that $\dot{\phi}$, $\dot{\theta}$ and $\dot{\psi}$ are *not* a mutually orthogonal vector triad, but are nonorthogonal components of $\bar{\omega}$. Referring to figure 5, relationships can be written between the body-axis rotational rates and $\dot{\phi}$, $\dot{\theta}$, and $\dot{\psi}$ by summing the orthogonal projections of $\dot{\phi}$, $\dot{\theta}$, and $\dot{\psi}$ onto the x, y, and z axes:

$$\begin{aligned} p &= \dot{\phi} - \dot{\psi} \sin \theta \\ q &= \dot{\theta} \cos \phi + \dot{\psi} \cos \theta \sin \phi \\ r &= \dot{\psi} \cos \theta \cos \phi - \dot{\theta} \sin \phi \end{aligned}$$

or conversely,

$$\begin{aligned} \dot{\psi} &= (q \sin \phi + r \cos \phi) \sec \theta \\ \dot{\theta} &= q \cos \phi - r \sin \phi \\ \dot{\phi} &= p + (q \sin \phi + r \cos \phi) \tan \theta \end{aligned}$$

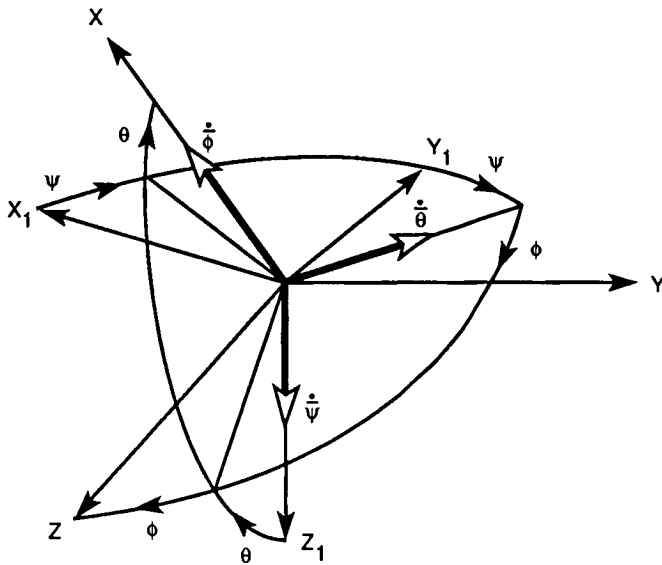


Figure 5. Euler angle rates.

Now with this last transformation we can change from the body-axis rotational rates to Euler angle rates. The Euler angle rates can be integrated with respect to time to yield the Euler angles, thus specifying the aircraft's orientation.

Keep in mind that the relationships are undefined at $\theta \pm (\pi/2)$. Though not presented here, there are methods of treating this singularity, if required.

Other Relationships

There are a number of other important relationships between the various state variables. Once the translational accelerations in the local frame are formed, they can be integrated once to obtain velocities and again for displacements. Thus,

$$\begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} = \int \begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix} dt$$

and

$$\begin{bmatrix} D_N \\ D_E \\ D_D \end{bmatrix} = \int \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} dt$$

The velocities can be transformed to the body-axis system to yield u , v , and w :

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = [L_{toB}] \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix}$$

Using the translational equations of motion that were written in the body-axis system, the body-axis accelerations can be solved for as follows:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} vr - wq \\ wp - ur \\ uq - vp \end{bmatrix} + \begin{bmatrix} F_x/m \\ F_y/m \\ F_z/m \end{bmatrix}$$

$$= \begin{bmatrix} vr - wq \\ wp - ur \\ uq - vp \end{bmatrix} + [LtoB] \begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix}$$

The body-axis velocities can be used to obtain the aircraft angles of attack and sideslip:

$$\alpha = \tan^{-1} (w/u)$$

$$\beta = \tan^{-1} [v/(u^2 + w^2)^{1/2}]$$

Equation Summary

Given that the forces and moments acting on the aircraft's c.g. have been summed, the translation dynamics are described by the following equations (where the primes indicate body-axis forces without gravitational terms):

$$\begin{bmatrix} F_N \\ F_E \\ F_D \end{bmatrix} = [BtoL] \begin{bmatrix} F'_x \\ F'_y \\ F'_z \end{bmatrix}$$

$$\begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix} = \begin{bmatrix} F_N/m \\ F_E/m \\ (F_D + \text{weight})/m \end{bmatrix}$$

$$\begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} = \int \begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix} dt$$

$$\begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} = \int \begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix} dt$$

$$\begin{bmatrix} D_N \\ D_E \\ D_D \end{bmatrix} = \int \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} dt$$

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} vr - wq \\ wp - ur \\ uq - vp \end{bmatrix} + [LtoB] \begin{bmatrix} \dot{V}_N \\ \dot{V}_E \\ \dot{V}_D \end{bmatrix}$$

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = [LtoB] \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix}$$

The rotational dynamics are defined by the following equations:

$$\dot{p} = \frac{I_{zz}}{D} L + \frac{I_{xz}}{D} N + \left[\frac{(I_{xx} - I_{yy} + I_{zz})I_{xz}}{D} \right] pq + \left[\frac{(I_{yy} - I_{zz})I_{zz} - I_{xz}^2}{D} \right] rq$$

$$\dot{q} = \frac{1}{I_{yy}} M + \frac{(I_{zz} - I_{xx})}{I_{yy}} pr + \frac{I_{xz}}{I_{yy}} (r^2 - p^2)$$

$$\dot{r} = -\frac{I_{xz}}{D} L + \frac{I_{xx}}{D} N + \left[\frac{(I_{xx} - I_{yy})I_{xx} + I_{xz}^2}{D} \right] pq + \left[\frac{(I_{yy} - I_{xx} - I_{zz})I_{xz}}{D} \right] rq$$

$$D = I_{xx}I_{zz} - I_{xz}^2$$

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \int \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} dt$$

$$\dot{\psi} = (q \sin\phi + r \cos\phi) \sec\theta$$

$$\dot{\theta} = q \cos\phi - r \sin\phi$$

$$\dot{\phi} = p + (q \sin\phi + r \cos\phi) \tan\theta$$

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \int \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} dt$$

Thus the aircraft's acceleration, velocity, location, and orientation are completely specified.

AIRCRAFT SUBSYSTEM MODULES

As was shown in figure 1, the various aircraft subsystems—for example, aero, landing gear, and engine—feed information into the general equations of motion. These subsystems are what distinguish a particular aircraft simulation from another and as such cannot really be generalized to any degree. A few of the subsystems will be discussed in terms of general approaches that are commonly taken in today's simulations.

The control system is an example of a subsystem for which it is difficult to generalize an approach. It usually has a primary, or direct, pilot input path and an augmenting or stabilizing path. The control laws may be implemented by either digital or analog circuits or both. The model might include a representation of actuator dynamics. In any case, the control system should be specified by system diagrams, logic statements, data values, gain schedules, etc. In the computer-program implementation of the control-system model there is a need to have a good transfer function solver that clearly handles the transition of state. Special care must be taken to assure that the temporal indices of variables within the control-system program are properly matched.

The engine system has become increasingly important to real-time simulations. The engine and the dynamics of the engine control system can interact

with the rotor dynamics via the rpm degree of freedom. Traditionally, engine models were very simple, usually representing only the torque dynamics. However, contemporary simulations are utilizing increasingly sophisticated engine models, models that incorporate internal engine states in order to more accurately simulate interactions with the rotor system (ref. 3).

Aerodynamic Model

To simulate the aircraft in all flight regimes, a fairly comprehensive, total-force aerodynamic model is usually required. The model should separate the various airframe components, such as fuselage, wings, empennage, and any other attachments. This separation allows the inclusion of local effects of the airstream such as rotor wake, wing downwash, air turbulence, and other disturbances. The most common approach to modeling the aerodynamic forces and moments is through the use of tables of aerodynamic coefficients.

The data are normally produced from wind-tunnel tests where lift, drag, and pitch moments are measured over a range of angles of attack and sideslip, and, if appropriate, Mach number. These basic data, in a variety of combinations and for various airframe components, make up the "aero data" for the simulation model.

The aero data are usually in dimensionless-coefficient form in the wind-axis system. These coefficients are computed by taking the force (lift or drag) and dividing by the term $\rho v^2 A/2$, where ρ is the air density, v is the velocity relative to the air mass, and A is a reference area (such as wing area). The moments are divided by $\rho v^2 A l$ where l is a reference length (such as wing cord). The wind axis differs from the body axis by rotations through the angles of attack and sideslip. It must be noted that there are many variations of the definitions of the coefficients and of the wind axis. A specific model must define the conventions being used.

The typical scheme for modeling the aero data is to define the local velocities, Mach number, and angles of attack and sideslip. If the horizontal stabilizer is taken as an example, the local velocity would be the velocity at the aircraft c.g., modified by body rotational rates and wake effects from the wing, fuselage, or rotor system or all three. The local angles of attack and sideslip are defined with respect to the local velocity components. Aerodynamic coefficients are found (interpolated) in the database using, for instance, the angle of attack and elevator deflection. The forces are found by multiplying the coefficients by the nondimensionalizing factors. The forces and moments are transformed through the angles of attack and sideslip to the body axis. In some cases, the equations for wind-axis forces and moments can become quite complicated as various influences are modeled. Sideslip, rate of change of downwash, and airstream blockages are examples. By modeling each airframe component separately, these special considerations can easily be included. Once all the aerodynamic forces and moments for each subsystem are modeled, they can be summed at the aircraft c.g.

Helicopter Main-Rotor Model

The rotor system model is usually the most complicated module of the entire simulation mathematical model. Historically, the rotor model was severely limited in complexity because of the computational difficulties involved in running the model in real time. With today's low-cost, high-speed computing systems, however, modelers are continually adding detail and new complexities to the main-rotor models. The rotor modeling methods are too involved to examine in any detail here, but their general aspects will be discussed.

Two modeling approaches are used extensively in simulations: the blade-element method, which is dominant in contemporary simulations, and the tip-path-plane method, which has a considerably reduced computational requirement (refs. 4-6). For the blade-element approach, the rotor-blade dynamics are represented by degrees of freedom in a rotating coordinate system that spins with the rotor itself. The forces and moments are defined in this rotating frame and summed at the hub. The tip-path-plane approach makes use of a Fourier transformation to represent the rotor dynamics in a nonrotating coordinate system. Essentially, the rotor is treated as a tilting disk, and forces and moments are described in this nonrotating frame. The discussion that follows will describe the general approach for the blade-element modeling method.

The rotor model can be divided into several submodules: the rotor-induced velocity, or inflow; blade dynamics; rotor forces and moments; and various coordinate transformations. The inflow model is the least exact submodule of the rotor model. The simple models in use today typically have a uniformly distributed component that is derived from momentum theory plus harmonically distributed components based on the periodic moments acting on the rotor disk. It is also common to impose a "dynamic" behavior to the inflow by using empirically derived time-lags.

The blade motions are represented by complex dynamic equations that are nonlinear and that have periodic coefficients. The blades move as rigid bodies about a specific hinge or bearing arrangement. Various elastic modes of blade motion can also be represented. From these equations, the blade velocities and displacements are known. Combining the blade state with the local velocities (airframe, rotor, and inflow), the blade loads can be described. In the blade-element model, the blade aerodynamic forces and moments are defined in a manner similar to those used in other areas of the helicopter aerodynamic model (described above). The blade is divided into a number of radially distributed segments (elements). For each segment, the local velocity and angle of attack are found. Tabulated values of section lift, drag, and pitch moment are interpolated to find the aero forces and moments at each segment. The forces and moments are summed along each blade and for all blades of the rotor.

There are a number of additional coordinate systems that can come into play with the rotor model. The axis system conventions differ depending on the physical arrangements of a particular rotor design. Typically there is an axis system that is a body axis aligned with the rotor shaft. There are various rotating-axis systems that progress from the hub, across the blade-hinge points, and out to the blade segments. Finally, there is a wind-axis system at each blade segment where the aerodynamic

forces and moments are defined. As one would imagine, it is absolutely necessary to carefully define each axis system and the transformations from one to another in the model.

With the availability of high-speed, parallel computer systems, new areas of rotor-system modeling for simulation purposes have become possible. Modelers are adding elastic modes to the blade dynamics and dynamic wake models to achieve a much higher fidelity representation of rotor inflow (refs. 7, 8). Combined, these advancements make possible a real-time, aeroelastic rotor model.

Tail-Rotor Model

The mathematical model of the helicopter tail rotor is usually much simpler than that of the main rotor. Again, modern high-speed computer systems allow tail-rotor models of greater complexity, but the benefits are not significant for most purposes. In most instances, it is sufficient to model the thrust and the required torque of the tail rotor.

A common method for representing the tail rotor in a simple fashion is through the use of the Bailey theory (ref. 9). This is a closed-form approach that uses parameters that only depend on blade pitch and the inflow ratio. A set of "t" coefficients is computed that are in turn used to calculate the thrust and torque required. After the thrust is resolved into body-axis forces and moments, torque can then be made available to a drive-train model.

Environmental Model

The simulation requires certain characteristics about the air mass. The aero and engine models require air density, pressure, and temperature. The aero model requires air-mass velocities including steady or variable winds and gusts, wind shears, and air turbulence. The first items are fairly standard and can be referred to as the atmospheric model. Simulations can use the standard atmospheric databases, "hot day" databases, or any collection of special ones (refs. 10, 11). The databases are usually interpolated with aircraft altitude to yield density, pressure, and temperature.

The velocity variations of the air mass are best modeled in two parts: the lower-frequency deterministic gusts, shears, and steady winds, and the higher-frequency random turbulence. The deterministic velocities are defined in the fixed (inertial) frame of reference and can be modeled as functions of time and spatial coordinates. A reasonable method of implementing these winds is to add them to the inertial velocities and to then rotate them to the body axis. These new definitions for the body-axis translational velocities, u , v , and w , make them "relative velocities," that is, relative to the wind. They are the velocities upon which aero forces and moments are based.

Air turbulence is usually represented by statistical models (ref. 2). These models typically assume the velocity variation to be random, isotropic, and with negligible cross-correlation between components. These models also assume

Taylor's hypothesis, or the frozen-field concept, which states that a patch of turbulence is constant or "frozen in time." Grossly stated, each component of turbulence is modeled by running a normally distributed noise signal through a shaping filter or correlation function. The Dryden and von Karman models are examples. These models use a characteristic scale length which can be taken as a wing span or a rotor radius. The turbulence models have been commonly used for fixed-wing aircraft and have been "forced" into rotary-wing models. Because of the rotating blades, however, these models are not really appropriate for rotary-wing applications. Recent work has attempted to improve the modeling for the case of rotational sampling of the turbulent field (ref. 12).

CONCLUDING REMARKS

This chapter has presented a discussion in general terms of the type of mathematical model used in a real-time flight simulation. The model used in simulations describes and specifies the dynamical behavior of the simulated aircraft. In turn, the dynamical behavior of an aircraft was shown to comprise all the various motions of the airframe and the states and performance of the various aircraft subsystems – for example, the engine. The model is best presented by, and is composed of, mathematical equations, schematic diagrams, logic diagrams, and tables and graphs of data including geometry, aerodynamic coefficients, and gain schedules.

The discussion of mathematical modeling for simulation covered the general equations of motion and the specific aircraft subsystems. The general equations of motion, which constitute the core of the simulation, were developed along with the equations that are necessary for predicting the aircraft's state when the external forces and moments are known. Some of the typical aircraft-specific modules were also examined in an effort to provide a general idea of what might be included in contemporary flight simulation models.

Modularity and standardization were recommended as being a proper approach to the development of simulation mathematical models. Standard conventions should be defined and adhered to in the design of all the modules, and the information interfaces among modules must be defined, as well as any interfaces to the "outside world." If this approach to modeling is practiced, subsequent maintenance of and modifications to the model can be accomplished efficiently.

SYMBOLS

D_N, D_E, D_D	aircraft position in the local-axis system, ft
\bar{F}	total external force acting on the aircraft, lb
F_x, F_y, F_z	components of the total external force acting on the aircraft in the x, y, and z directions, respectively, lb
F_N, F_E, F_D	components of the total external force acting on the aircraft in the local-axis system, lb
g	acceleration due to gravity, ft/sec ²
\bar{H}	the angular momentum, ft.lb.sec
I_{xx}, I_{yy}, I_{zz} I_{xy}, I_{xz}, I_{yz}	moments and products of inertia, lb.sec ² .ft
$\hat{i}, \hat{j}, \hat{k}$	orthogonal triad of unit vectors aligned with the x, y, and z body axes, respectively
L, M, N	components of total moment about the x, y, and z directions, ft.lb
m	the aircraft mass, slugs (lb.sec ² /ft)
\bar{M}	total external moment acting at the center of mass, ft.lb
p, q, r	the body-axis rotational velocities about the x, y, and z axes, respectively, rad/sec
u, v, w	the body-axis translational velocities in the x, y, and z directions, respectively, ft/sec
\bar{v}	the absolute velocity of the center of mass, ft/sec
V_N, V_E, V_D	aircraft velocities in the local-axis system, ft/sec
x, y, z	the body axes; origin at the aircraft CG, the x-axis is pointed forward out the nose; the y-axis is pointed out the right side of the aircraft, and the z-axis is directed down through the underside of the aircraft

X_L, Y_L, Z_L	the local axes; origin at the aircraft's c.g. with a fixed orientation; the X_L -axis always points north, the Y_L -axis points east, and the Z_L -axis points down
X_E, Y_E, Z_E	the inertial axes; origin fixed at some point on Earth's surface; X_E -axis always points north, the Y_E -axis points east, and the Z_E -axis points down.
α	aircraft angle of attack, rad
β	aircraft sideslip angle, rad
ϕ, θ, ψ	Euler angles describing the aircraft's orientation; ϕ is the roll angle, θ is the pitch angle, and ψ is the yaw angle, rad
$\bar{\omega}$	the aircraft's total angular velocity, rad/sec

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9 SIMULATION VALIDATION IN THE FREQUENCY DOMAIN

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SUMMARY

Frequency-domain parameter-identification techniques were used to develop a hover mathematical model of the AH-64 Apache helicopter from flight data. The unstable AH-64 flight characteristics were parameterized in conventional stability derivative form. To improve the model's vertical response, a simple dynamic inflow approximation was added. Additional vehicle subcomponents, such as the engine and stick dynamics, were also modeled. The model was then evaluated by AH-64 pilots in a moving-base simulation. Pilot opinion was that the simulation was a satisfactory representation of the aircraft for the tasks of interest.

INTRODUCTION

Validation of fixed-wing simulation models in civil transport training simulators is accomplished by comparing mathematical model time-responses with flight-test time-responses. The FAA specifies tolerances for the allowable differences in these time-domain comparisons, and, to date, these tolerances have served their intended validation function.

The same general method of validation, that is, using time-domain validation, has been proposed for helicopters. Although this approach appears logical based on experience with fixed-wing aircraft, there may be difficulties in its application. Four of those potential difficulties are mentioned briefly here. The first such difficulty is related to stability. At low speeds, unaugmented helicopters are inherently unstable, and it can be quite challenging to credibly compare flight with simulation. Initial conditions must closely match, and the inevitable flight-test instrumentation biases create further complications.

A second difficulty is the multi-input/multi-output nature of the problem. Some helicopters, such as the Bk-117 with its hingeless rotor, have considerable coupling. A unit longitudinal input produces as much vehicle roll-rate response as it produces pitch response. As a result, for a pilot to control the vehicle about the nominal operating point, simultaneous inputs occur in all axes.

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A third difficulty is that the time-domain validation procedure does not typically address the root cause of poor model fidelity. After the pilot has stabilized a helicopter with his control inputs, the resulting stability margins may not be large. Pilots are very sensitive to further degradations in these stability margins, which are calculated in specific regions of the frequency domain. The corresponding regions in the time domain usually correspond to differences in the initial response (such as the initial delay in response following a step input; many inconsistent methods exist in the time domain for measuring such delays). So in the time domain, these small differences may be critical to the pilot, but might not be a compelling mismatch from the time-history traces.

A fourth difficulty has to do with time-response mismatches. In that event, the modeler may be left with little insight into what to modify in order to improve the comparison. Since the time response to a step input is a sum of the vehicle response at all frequencies, modal separation is not self-evident, and it can be difficult to attribute the causes of poor fidelity.

A list of symbols and the tables and figures appear at the end of this chapter.

BACKGROUND

The above problems are mitigated by moving from the time domain to the frequency domain. Unstable systems may be compared, multi-input/multi-output problems are elegantly handled, vehicle fidelity is measured in the region of pilot interest, and root causes of model mismatches are more easily identified. However, to date, the problem with using frequency-domain-based validation has been the lack of a complete set of tolerances that can be confidently applied in the comparisons.

What follows, although considerably revised and selectively extracted, is in essence a reproduction of reference 1, and is reprinted here by permission of the AIAA. Reference 1 is a paper that the authors originally presented at an AIAA Atmospheric Flight Conference in 1991.

In reference 1, the authors described the development of a hover model for the AH-64 Apache helicopter. The model was developed by combining an analysis of the pertinent physics with an empirical accumulation of acquired flight data. It is presented here because it serves as a valuable first step toward making valid frequency-domain comparisons. The discussion does not suggest generic frequency-domain boundaries that can be applied to any helicopter simulation, but it does illustrate the technique, as well as provide one data point for frequency-domain differences that were deemed acceptable in piloted simulation.

The hover model was developed to support the design of hover-display dynamics for the Apache. Accurate vehicle-response models are used in two ways for current methods in hover-display design. First, they are used to provide predictive velocity information on the pilot's display, thus greatly improving the display's utility to the pilot. Second, the availability of an accurate model allows a credible analytical evaluation of the pilot-vehicle-display closed-loop dynamics during display design trade-offs prior to the piloted evaluation (refs. 2, 3).

Different levels of model complexity are available to accomplish the design and evaluation. A full-envelope, rotor-map mathematical model of the AH-64 exists and has been compared with flight data (ref. 4). This complex model has the difficult goal of matching the vehicle characteristics over the full flight envelope. It is shown in reference 4 that whereas the model is adequate in pitch and yaw for primary axis inputs, it is deficient in certain respects when used to predict the primary roll and vertical responses, as well as pitch/roll cross-coupling.

Instead of using the complex full-flight-envelope model for the study described herein, the authors decided to develop a simpler model that more closely matched the on-axis and off-axis flight characteristics in the restricted hover/near-hover flight regime of interest for the display research. The model developed was an extended six-degree-of-freedom (DOF) stability-derivative characterization extracted from an extensive flight data base using system-identification techniques.

There were four reasons for taking this approach. First, Ames Research Center has developed and applied procedures for easily identifying multi-input/multi-output models using frequency-domain techniques (refs. 5-8). These techniques are now assembled in a package called Comprehensive Identification from Frequency Responses (CIFER[®]). Second, a parametric, linear model (such as a low-order transfer function) eases the display design. Otherwise, it would have been necessary to derive this extracted model from the complex nonlinear model by using methods similar to those described herein for the flight-test data. Third, previous attempts to develop bare-airframe-unstable-helicopter models at hover have been generally unsuccessful because of poor data or because of difficulties in applying the identification method. The availability of a newly acquired and comprehensive data base for the AH-64 and the recently completed CIFER[®] system presented an opportunity to advance the state of the art in helicopter system identification. Fourth, once a model is developed with the Apache's Digital Automatic Stabilization Equipment (DASE) off, that is, a DASE-off model, the DASE can be easily added by wrapping the known control laws around the DASE-off model.

As part of a vehicle development process, many simulation models are developed before the first flight. These models typically follow an evolutionary process and are updated and expanded as flight data are generated. The availability of a complete AH-64 flight-test data base allowed an alternative approach that uses system-identification techniques and knowledge of the AH-64 principal flight dynamics to extract a new simulation model based entirely on flight data.

IDENTIFICATION METHOD

The frequency-domain system-identification method described in reference 7 and shown in figure 1 was applied here. The identification process comprises three major steps: (1) the identification of the correct output/input nonparametric frequency responses, (2) the development of a parametric state-space stability-derivative model that best matches the frequency responses, and (3) the verification of the resulting stability-derivative model with flight-data responses not used in the identification process.

The first of these steps is accomplished by having the pilot generate a progressive low-to-high-frequency stick input over the frequency range to be modeled (ref. 6). For the Apache data taken, this range encompasses 0.1-30 rad/sec. The input is such that the vehicle starts and ends in trim. A fast-Fourier transform, using chirp z-transforms (ref. 9), is calculated from these data for each input/output combination. The matrix of frequency responses between the input "x" and the output "y" is determined by multiplying the inverse of the input spectral-density matrix by the cross-spectral-density matrix,

$$H(\omega) = [G_{xx}(\omega)]^{-1}G_{xy}(\omega) \quad (1)$$

This matrix calculation yields the correct single-input/single-output frequency responses when multiple control inputs are present and partially correlated in the test data, which is usually the case for helicopter tests. For single-input tests, equation (1) reduces to the more familiar scalar relationship. After these frequency responses are calculated, the second step is to hypothesize a state-space stability-derivative model based on a physical understanding of the vehicle's primary flight dynamics. An optimization scheme employing a secant search then minimizes the error in both magnitude and phase between the free model parameters and the frequency responses. Confidence analyses are performed on each converged result by using the following theoretical accuracy metrics: Cramer-Rao bounds, insensitivities, and correlations between free model parameters. Insensitive parameters and selected parameters in those sets that are highly correlated are eliminated, and the optimization scheme is repeated (ref. 7).

The third and final step, after a satisfactory model has been determined, is to drive the model with flight-test doublet inputs (which are not used in the identification process) for comparison with flight-test responses. This final step is a verification of both the model structure and its values.

AIRCRAFT IDENTIFICATION

Vehicle

Figure 2 (from ref. 10) shows the principal dimensions of the AH-64 Apache. It is a single-main-rotor, twin-engine, tandem-seat, aerial-weapons platform. The flight data were collected at the U. S. Army's Airworthiness Qualification Test Directorate in 1990. The aircraft gross weight at takeoff was 16,100 lb with the c.g. at 204.4 in. Ambient temperature and pressure were 58° F and 30.06 in.Hg, respectively. The vehicle was configured with eight Hellfire missiles inboard and two 19-shot pods outboard. Data were taken out of ground effect with the DASE on and off.

Frequency-Domain Data

Frequency sweeps were input in each axis separately while data were recorded for four inputs and eight outputs. An example of the flight data used to generate frequency responses for the model determination is shown in figure 3. The aircraft-vertical-body accelerometer signal is shown as one of the eight outputs, with

the cockpit-collective lever as the input. Here the mean and slope are removed from the data for the spectral calculations.

The identified $a_z(j\omega)/\delta_{col}(j\omega)$ frequency response of the aircraft is shown in figure 4. Here the effects of the a_z response owing to the other three cockpit control inputs have been removed by equation (1). The bottom plot in figure 4 is the partial coherence function, which is a measure of the linearity between the input and the output; it shows that a good frequency-response identification was achieved in the frequency range of 0.15-25 rad/sec for this input/output pair (ref. 7).

Important dynamic information may be obtained from the frequency-response plot shown in figure 4. Over a broad frequency range (0.2 - 3 rad/sec) the magnitude response is flat (14 dB) and the phase curve is -180° . These characteristics show that positive (up) collective stick inputs produce a constant upward (negative Z-axis) acceleration of $a_z/\delta_{col} = -5.3 \text{ ft/sec}^2/\text{in}$. At high frequency, the significant peaking in the magnitude response reflects the effect of the rotor's coupled flap/inflow dynamics (a discussion of dynamics may be found in ref. 11), whereas at low frequency, the magnitude attenuation (and phase increase) reflects the quasi-steady vehicle heave damping. Thirty-two such AH-64 hover frequency responses for eight outputs from four inputs were identified. The eight outputs are u , v , p , q , r , a_x , a_y , and a_z . The four inputs are δ_{lon} , δ_{lat} , δ_{ped} , and δ_{col} .

Of these 32 responses, 18 were selected for the stability-derivative identification using the coherence function as the primary indicator of the response's relevance for the model. For example, no pitch-rate coupling results from pedal input, so this response pair has very poor coherence (no input-to-output transfer). Thus, q/δ_{ped} was not used in the model determination. The responses that were used in the model development are shown in the table below. Although, in many instances, the flight data had spectral content out to 30 rad/sec, the identification range for this 7-DOF (six rigid-body degrees of freedom and one for dynamic inflow) model typically extended only to 10 rad/sec (except for the vertical axis, which is discussed later). This maximum frequency is usually acceptable for flight-simulation handling-qualities investigations.

	Lon.	Lat.	Ped.	Col.
u	✓			✓
v		✓	✓	
p		✓	✓	
q	✓	✓		
r		✓	✓	✓
a_x	✓	✓		✓
a_y		✓	✓	✓
a_z				✓

The stability derivatives that best match the set of 18 DASE-off frequency responses generated from the flight data are given in tables 1 and 2. Table 1 is a list of the system derivatives, and table 2 is a list of the control derivatives. Also listed are identified time-delays for each axis that approximate the unmodeled high-frequency modes, such as the swashplate actuators and the main-rotor dynamics. Table 3 summarizes the resulting 9th-order model. The identified delays for each input are shown at the bottom of the table. The lead/lag filter on the collective term into the vertical axis is an approximation of the dynamic inflow to be discussed later.

Example comparisons of the flight and model frequency responses are shown in figure 5. The best and worst fits in the frequency domain, as well as two principal on-axis-angular responses, are shown. The a_y/δ_{ped} response is the best fit, and the q/δ_{lat} response is the worst fit. The quality of all the remaining 16 fits lies between these two bounds.

Time-Domain Data

Figures 6-9 compare the time-responses predicted by the flight-identified model (referred to as "flight linear") with both flight-test data and with a linearized six-degree-of-freedom model extracted from the full-flight-envelope model of reference 4 (referred to as "complex linear"). The complex-linear model was extracted from the nonlinear complex model by using a forward difference method. Each figure in succession depicts responses to longitudinal (fig. 6), lateral (fig. 7), directional (fig. 8), and vertical (fig. 9) doublets. These flight data were not used in the flight-linear identification; as a result, they are a good indication of the flight-linear model's fidelity. For the longitudinal input in figure 6, both the on-axis (q/δ_{lon}) and the off-axis (p/δ_{lon}) angular responses of the flight-linear model match the flight data well. The longitudinal-acceleration response of the flight-linear model is almost identical to the flight-test response. Though the on-axis responses of the complex-linear model match the flight data well, the off-axis response is out of phase with the flight-test input.

Figure 7 shows the responses to lateral-cyclic inputs. The roll angles for both linear models have a mismatch at the start, but both roll-rate responses match well. Again, the complex-linear model off-axis responses are out of phase, and the flight-linear model matches well. The complex-linear model underpredicts the lateral-acceleration response, but its roll-angle response is slightly better than that of the flight-linear model. The flight-linear correlation is good even for the q/δ_{lat} response, which had the poorest relative fit in the frequency domain. For this lateral doublet, the spectrum of this input has its predominant power in the frequency-range of 1.6 rad/sec and higher; the frequency-response fit is good in this range. This time-domain matching would most likely be worse if a lower-frequency doublet was used, since for this case the model errors increase at low frequencies (less than 1 rad/sec).

The flight-linear model response to directional inputs (fig. 8) captures the on-axis yaw rate (r/δ_{ped}) with an excellent match. The flight-linear roll-rate response also matches well; this response is primarily caused by the vertical displacement of the tail rotor from the roll axis. The complex-linear model again matches the roll-attitude response better than the flight-linear model, but it does not match as well in p , r , and a_y .

The flight-linear vertical-axis-acceleration response in figure 9 matches the overshoots in the flight data almost perfectly; the overshoots are due to a dynamic inflow effect. Note that the flight-linear model has a low value of Z_w (-0.122 sec^{-1} in table 3). The vertical-acceleration response is consistent with this low value, for the acceleration does not decay over the 2 sec of doublet input, as would be expected with a $Z_w \approx -0.3 \text{ sec}^{-1}$ that is typically determined from momentum theory. Other identification efforts have noted this reduction in identified Z_w when compared with momentum theory (ref. 12). The omission of the effect of varying rotor speed Ω on thrust might contribute to this discrepancy. For this modeling, an assumption of constant Ω was used. The complex-linear model captures the peak magnitude in the a_z response, but it does not match the rest of the dynamics; this is because another state is required, as will be described later. The angular responses of the complex-linear model to collective do not match as well as those of the flight-linear model.

Notice that while the on-axis responses of the complex-linear model shown here are satisfactory (except for vertical), the principal deficiencies are in the off-axis responses. These trends are consistent with those noted above, which adds confidence in the linear characterization of the nonlinear model for comparison purposes. The time-responses show that for this restricted flight regime, the flight-linear model is a better representation of the principal flight dynamics than is the complex-linear model extracted from the complex-nonlinear model. This is important, because the trend in vehicle modeling is toward using the most complex model available, whereas at times a simple model may be more accurate over the frequency range of interest.

Dynamic Inflow Addition

The modeling of the effect of dynamic inflow in the vertical response was initially neglected. Dynamic inflow accounts for the fact that the induced velocity change at the rotor does not occur instantaneously (ref. 13). The dynamic lag associated with the acceleration of a large air mass results in an angle-of-attack change at the rotor blade. For a collective input, the angle-of-attack perturbation is initially caused by the immediate collective pitch change; this initial angle of attack is reduced by the change in inflow during the climb, which in turn results in more initial thrust than steady-state thrust. This increase in initial thrust is reflected in the high-frequency peaking of the a_z/δ_{col} magnitude plot of figure 4. Dynamic inflow has previously been approximated with an equivalent system model that adds a lead term (a zero) and a pure delay in the w/δ_{col} response (ref. 12). The same method was applied here, except that the addition of a zero was accompanied by a pole instead of a pure delay. Over the frequency range of interest (less than 25 rad/sec), this approximation was deemed acceptable.

The nonstandard extra terms M_{apz} , Z_{wa} , Z_{tht} , and Z_{tzl} in tables 1 and 2 were added to the parametric structure to model the dynamic inflow effect. Table 4 shows how the transfer function of the combined quasi-steady heave damping with a pole-zero addition maps into the variables defined in tables 1 and 2. The identified result was converted back into a lead/lag filter on the collective input to the vertical equation and an effective heave damping. The conversion was made in order to prevent an unreasonable disturbance-rejection response to perturbations in heave velocity.

The effect of the addition of the lead/lag filter in the vertical axis is shown in figure 10 in the "before" and "after" plots. The values in the collective lead/lag filter are given at the bottom of table 3. The "before" dynamic-inflow plot was developed using an a_z/δ_{col} frequency-response fit range up to 10 rad/sec. As shown, the sharp initial overshoot is not captured with the 8th-order model without the dynamic-inflow approximation. Pilots will often note in moving-base simulations that they do not feel a "kick in the pants" on the initial collective input. In the "after" dynamic inflow plot, the a_z/δ_{col} fit range was extended to 25 rad/sec, and the lead/lag filter is included in the parameterization of the model. Note that this simple approximation captures the initial overshoot almost perfectly, whereas the fit is slightly sacrificed after the overshoot. The effect of this lead/lag filter in the vertical axis is stabilizing for height control here, since the pilot-in-the-loop phase margin is improved. This improvement was noticed immediately during the initial development using fixed-base evaluations.

Control System Addition

It should be emphasized that this stability-derivative model is for the hover environs only and is valid to less than about 15 knots. For this near-hover flight regime, the AH-64 DASE control system was closed around the 8th-order stability-derivative model with the dynamic-inflow approximation. The diagrams of the pitch, roll, and yaw DASE are given in reference 14. This control system, in its primary mode, uses a shaped combination of high-passed pilot stick-and-pedal positions and angular-rate feedbacks. The DASE is a limited-authority (approximately 10% of the actuator authority in each axis) series system. Time-history comparisons between flight test with the DASE-on and the model with the DASE-on are shown for each axis in figures 11-14. Doublets of the type shown in figures 6-9 were the inputs in these comparisons.

As shown in figures 11-14, the on-axis responses match well for all axes, especially for the directional and vertical axes. One side of the model pitch-rate response to a longitudinal doublet is underpredicted; however, the model matches well on the other side of the doublet. One side of the model roll-rate response to a lateral doublet is more sensitive than in flight, but the character of the response is similar.

Comparisons of the off-axis responses with DASE-on are generally good. The roll-rate-to-pedal input has the most striking similarity to that of the aircraft. The roll rate due to pitch input has the correct sign and magnitude, but the model leads the aircraft throughout the response. The DASE suppresses most of the pitch rate to lateral inputs.

SUBCOMPONENT IDENTIFICATION

Engine

To add realism to the later described simulation, a torque and rotor-rpm model was identified from the flight data. First, a simple physical model was formulated

(fig. 15). Three elements were used for the model: the engine, the rotor shaft, and the blades. The engine produces a torque on the shaft, which acts through the lightly damped lead/lag spring and damper between the shaft's hub and the in-plane deflection of the rotor blades. Feedback of the power-turbine speed, which is physically measured at the engine output shaft, is sent to the engine for regulation. For conditions when the rotor is being driven by the power turbine, instead of windmilling, rotor speed and power turbine speed are directly related by the gearing ratio between them. Thus, a feedback of rotor speed, instead of power-turbine speed, is shown. Collective displacement causes a drag perturbation on the blades, and an anticipation signal from the collective is sent to the engine for mitigation of rotor-speed loss from the increased drag. Only collective was used to induce torque and rpm variations for this hover simulation. Furthermore, the model was decoupled from the airframe dynamics; thus the effects of rpm on thrust and of yaw rates on rpm were not modeled. The purpose of the model was to drive gauges in the simulator cockpit and on the display in a realistic manner.

The simple block diagram at the top of figure 15 is expanded into the physical-variable form at the bottom of the figure. The engine-torque response was modeled as a first-order actuator. Integral action in the engine controller, although typically present, was not necessary for the modeling. This parametric structure was used to match the flight data.

The resulting model is given in table 5; frequency and time-response comparisons between flight and the model are shown in figures 16 and 17. It can be seen that the principal characteristics are well captured by the somewhat simple physical model. The identification reveals the dominant coupled rotor-lead-lag/shaft-and-transmission mode of the system that causes closed-loop engine control in helicopters to be of low bandwidth. This lightly damped mode was identified at 2.7 Hz. This frequency is the same as that documented in reference 15 for the UH-60 and requires special attention for engine/rpm control.

Stick Dynamics

An element of simulation that typically receives little attention is the stick dynamics. Most simulations try to match static force/deflection characteristics, damping ratio, and free play, but few simulations try to match the inertia of the stick and its associated linkages. Inertia can be matched if a simulator's stick force-feel system uses force feedback. Stick inertia for helicopters has been shown to have an important effect on pilot opinion (ref. 16), and the resulting stick-displacement-to-force bandwidth is a topic of interest in the contemporary helicopter-handling-qualities community (ref. 17).

For this experiment, static and dynamic data from the AH-64 were used to derive the static and dynamic stick characteristics. The nonlinear equation for stick force as a function of stick position is shown in table 6 along with the identified physical parameters. The gradient, preload, and friction were identified from plots of static force and position. The amount of free play was based on measurements and pilot comments. The dynamic data, consisting of stick free-releases from half-of-full deflection, were used to identify I_s and B_s by matching time-histories.

The actual simulated cyclic stick friction and inertia differed slightly from the identified parameters. Because the stick data were measured with the rotors stopped, the resulting friction was a relatively high 0.3 lb. In flight, rotor-system vibration adds dither to the linkages, effectively reducing static friction. Estimates of flight friction levels of 0.1 lb were used in the simulation. Pilot comments indicated this was reasonable. The ability of the simulator's force-feel system to match effective inertia by increasing gain was limited by hydraulic-system stability. The achievable simulator inertias are listed in table 6 as well.

Dynamic comparisons for longitudinal, lateral, and directional free releases are shown in figure 18. The aircraft releases are plotted against both the identified responses (AH-64 fit) using the parameters in table 6 and the achieved responses (Vertical Motion Simulator) in the simulation. Note that the longitudinal stick is underdamped, and that because of inertia differences the achieved simulation response has a lower natural frequency than that of the aircraft. The simulated lateral and directional responses closely match those of the aircraft.

MODEL EVALUATION

Simulation Setup

The Vertical Motion Simulator (VMS) at Ames Research Center was used for subjective model evaluation. This large-amplitude motion system has linear displacements of ± 30 ft, ± 20 ft, and ± 4 ft in the vertical, lateral, and longitudinal degrees of freedom, respectively. The pitch, roll, and yaw angular displacements are $\pm 18^\circ$, $\pm 18^\circ$, and $\pm 24^\circ$, respectively.

The simulation environment is shown in figure 19. From left to right, the pilot puts a force into the stick, which displaces according to the identified-stick-model characteristics. Cockpit-stick displacements then drive the 7-DOF model. The collective also drives the torque/rpm displays through the identified model. Model outputs are fed back through the DASE control laws, and are then washed out (high passed) before being sent to the motion system. These high-pass filters will be discussed later. Aircraft states are also sent to the Singer-Link DIG 1 four-channel visual system which sends three channels to the three cockpit windows and one to a helmet-mounted display (HMD). The aircraft states are processed to drive superimposed symbols on the HMD. The delay in the visual channel is 103 msec; visual-scene-time-delay compensation was not available for this simulation, a result of the use of the head-tracked forward-looking-infrared (FLIR) image presentation on the helmet-mounted display. From these simulation elements, the pilot receives four principal cues: (1) vehicle-motion cues, (2) visual-scene cues, (3) display-symbol cues, and (4) stick-position and force cues. Also present was simulated AH-64 cockpit sounds, which were produced with a digital synthesizer driven by torque and rpm data.

Since motion of the simulator cab is restricted by the limits noted previously, digital-high-pass filters attenuate model accelerations before they are sent to drive the motion system. The principal motion washout filters for the angular and linear axes are shown in figure 20 (other motion logic such as roll/sway coordination

will not be discussed). The filters are second-order with a damping ratio of 0.7. For this experiment, the high-frequency gain was set to 1.0 for all filters.

Thus, at frequencies beyond the filter natural frequency, the pilot will feel the full accelerations that the mathematical model is calculating. For low-frequency longitudinal and lateral accelerations from the model, the motion system slowly tilts to use gravity components to simulate the applied forces. For the remaining four axes, at frequencies below the natural frequency, the pilot feels less acceleration with an accompanying phase distortion. When assessing the fidelity of the model, these filter values are quite important. Their characteristics may be superimposed on frequency responses such as those shown in figure 5 to assess which part of the vehicle spectra the pilot feels. Below the washout natural frequency, the pilot must determine the fidelity of the mathematical models by using visual cues.

After the high-passed-motion commands are determined, they are sent to the motion hardware. The motion system is a large actuation system with its concomitant lags. The lags of the motion system in the pilot's four control axes (pitch, roll, yaw, and vertical) were modeled as effective time-delays, and values were identified from simulator data. Rather than add the time delays of the mathematical model identified in table 3 to the unavoidable motion time-delays, the motion-delay compensation method of figure 21 was used. Here, the mathematical-model delay was split into forward- and feedback-loop components. The sum of the two components equaled the identified-aircraft time-delay to allow the DASE control loops to operate on the flight-identified amount of delay (the delay that the DASE approximately sees in the aircraft).

To minimize the time-delay between pilot input and motion system response, as much of the motion delay as possible was placed in the mathematical-model feedback loop. The bottom of figure 21 shows the delays for each block. Note that the motion-system delay in the yaw and vertical axes exceeded the identified mathematical-model delay. Thus, for these two axes, the forward-loop delay was zero, and all of the identified delay was placed in the feedback loop. For the vertical axis, this effect resulted in an extra 83 msec of delay being present relative to the flight data. This redistribution also partially compensated for the visual delay in the forward control path, since the visual system receives its input from the same place (fig. 21) as the motion system.

The simulation was flown by 11 pilots, four of whom were qualified in the AH-64. Of the four AH-64-qualified pilots, three were from the U. S. Army and one was from McDonnell Douglas. The pilots performed several maneuvers, including precision hover, pedal turns, bob-ups, and side-steps. Ideally, one would like to evaluate the model against an actual vehicle in a back-to-back simulation and flight test for a precisely defined task. Then, pilot-vehicle performance comparisons between simulation and flight plus subjective pilot opinion ratings could be gathered. Here, the evaluation of the model was secondary to the simulation's primary objective of display design and evaluation. Also, an AH-64 was not available for use in back-to-back testing. Thus, pilot comments based on recollection of the vehicle's flying characteristics are the basis for assessing the model's fidelity. However, one

pilot was able to fly the simulator, then examine some particular items later in an aircraft flight, and then return to the simulator for another session.

Pilot Comments

The interested reader is referred to reference 1 for complete coverage of pilot comments about the fidelity of this simulation of the AH-64. What follows here is only the briefest summary of those comments and is intended to do no more than set the tone of pilot opinion of the simulation.

All the comments listed in reference 1 are from the four pilots who were qualified in the AH-64, and relate to their flying near-hover maneuvers at speeds up to 15 knots. In most instances, the pilots were presented with the FLIR image and symbols superimposed on the HMD.

In general, the pilots thought the simulation was a realistic representation of the AH-64, both in model behavior and workload. *In pitch*, there were comments about a tendency to pilot-induced oscillations (PIOs) with the DASE off, and a less sensitive attitude response with the DASE on. *Regarding roll*, the pilots reported no PIO tendency with the DASE off, although the aircraft does have such a tendency, and with the DASE on the simulation was thought to be more damped than the aircraft. *In yaw*, the comments were generally favorable, with the simulation reported as being like the airplane, in that the airplane "seems to wrap up in yaw for a control input and build to a point where you have to recover." *The vertical response* to collective was considered good, but the vertical rates were seen to be excessive in the simulation relative to those in the aircraft, and the workload to be greater in the simulator.

Although there were some negative comments (e.g., about responses in the vertical axis), the overall impression of the model was favorable. As expected, the pilots had difficulty in attributing deficiencies to specific locations within the simulation, which results from their indirect observation of what the mathematical model is actually doing. Their contact with the model, relative to what they sense in the aircraft, is through imperfect visual and motion cues.

For the visual cues, the simulation visual scene was devoid of texture and had a 103-msec time-delay. For motion cues, the motion system can only represent motion fidelity above the natural frequencies of the washout filter. In addition, as mentioned earlier, the directional and vertical axes suffer from hardware delays that are in excess of those identified for the mathematical model. These visual and motion effects are mentioned not to lay blame for simulation deficiencies elsewhere than on the mathematical model, but to point up the fact that these other system deficiencies will have an effect on the performance of even a perfect model. Quantification of some of these degrading effects has been examined in previous experiments (ref. 18).

The material that follows is presented in reply to and in way of explanation of some of the more pertinent pilot comments about the simulation. The discussion is presented in terms of specific comments that are not necessarily those mentioned in the brief summary above.

As a general comment, a pilot remarked that the simulation was difficult to smooth, and that it felt like a "rocky rowboat." This may be a result of imperfect phasing between the angular and linear motions. The simulation center of rotation is below the pilot, so linear motion has to cancel the resulting angular-induced linear motion. Although compensation in software is designed to match the responses, some jerkiness is present. There was another comment that "Outside approximately 6 knots, the model comes apart." That boundary on the model may have been chosen by the pilot, because the display evaluation tasks were designed to keep a displayed velocity symbol within its limits on the display, which was 6 knots.

The PIO tendency in pitch with the DASE off does not appear, upon examination, to be a result of a deficiency in the mathematical model. We can see from figure 5 that the model-phase response is even slightly better than that of the aircraft. With the DASE on, figure 11 reveals less q/δ_{lon} sensitivity, which is consistent with the pilot comments. The trim attitudes in pitch and roll were taken directly from stable hover flight data. The trim attitudes used were 6.5° of pitch and -2.5° roll. These trims did vary in the flight data as winds and weight changed; there may also be instrument biases.

No conclusion can be drawn from differences in the p/δ_{lat} responses of figure 5 that would explain differences in PIO tendencies. One might attribute the increased PIO tendency in pitch to a simulation artifact, but that conclusion would be inconsistent with a decreased PIO tendency in simulation for roll. The pilot recognized some motion-system effects, such as those discussed earlier, regarding roll.

Good comments on the yaw sensitivity are consistent with both the DASE-off and DASE-on plots (figs. 8, 13). The coupling from collective in figure 14 appears in the yaw-axis regulation. For a long period, relative to the aircraft yaw-rate trace being around zero, the simulation trace does not remain around zero. Pilots noticed and disliked this characteristic in the simulation, and, although it would seem to be a DASE-simulation problem, no errors were found during verification of the DASE. A positive comment on DASE-off coupling from collective is consistent with data shown in figure 9, except the model leads the aircraft because of unmodeled dynamics that couple between the rotor rpm and the yaw axis.

The vertical acceleration response sensitivity is consistent with the responses shown in figures 10 and 14. Other comments in this regard refer to the perceived (and actual) poor vertical damping of the mathematical model. A consistent comment concerned pilot inability to set a torque that would stabilize altitude. This comment appears to indicate that the pilot is trying to fly when out of ground effect with in-ground-effect techniques. Ground effect was not included in the simulation, because the tasks and evaluations were performed at a height of one rotor diameter from the ground, a height at which ground effect is minimal. When out of ground effect, the torque reading is effectively an acceleration command. Even with a vertical damping typically predicted from momentum theory (-0.3 sec^{-1}), pilots would not be able to maintain tight altitude control out of ground effect by setting torque. So some of the negative comments on the vertical axes may have been technique-related, since hovering operations are typically conducted at heights at which there is some help from ground effect in height stabilization. This explanation may not of itself be adequate, however, since

achieving acceptable simulated height dynamics that also match flight data has been a persistent problem.

CONCLUSIONS

A seven-degree-of-freedom rigid-body hover model of the AH-64 Apache helicopter was developed using frequency-domain system identification techniques on flight data. The model is applicable to any handling-qualities hover simulation.

Additional vehicle subcomponents, such as engine and stick dynamics, were identified. The model was evaluated by four AH-64 qualified pilots. Overall impressions of the model were favorable, with the most consistent negative comment relating to difficulty in maintaining height control. The mathematical model should be useful to future control and display designers as one that satisfactorily represents a current-generation helicopter in hover.

SYMBOLS

a_x, a_y, a_z	longitudinal, lateral, vertical applied specific force, ft/sec ²
B_s	stick damping, lb·sec/in ²
del	delayed
F_s	stick force, lb
I_s	stick effective inertia, slugs
j	complex variable, $\sqrt{-1}$
K_s	stick spring gradient, lb/ft
L, M, N	roll, pitch, yaw applied specific moments, rad/sec ²
lon, lat, ped, col	longitudinal, lateral, directional, vertical cockpit inputs, in.
M_{apz}	internal system derivative for dynamic inflow identification, 1/sec
p, q, r	roll, pitch, yaw angular rate perturbation, rad/sec
torque	torque referenced at main rotor, ft·lb
u, v, w	longitudinal, lateral, vertical airspeed perturbations, ft/sec
X, Y, Z	longitudinal, lateral, vertical applied specific force perturbations, ft/sec ²
x_1	rotor-blade velocity perturbation, rad/sec
x_2	rotor-blade position perturbation, rad
x_3	rotor-shaft and hub velocity perturbations, rad/sec
x_4	rotor-shaft and hub position perturbations, rad
x_5	main-rotor torque perturbations, ft/lb
\ddot{x}, \dot{x}, x	stick acceleration, ft/sec ² ; velocity, ft/sec; position, ft
Z_{tht}	internal control derivative inflow identification, ft/sec ² /in

Z_{tzl}	internal control derivative inflow identification, ft/sec ³ /in
Z_{wa}	internal systems derivative for dynamic inflow identification, 1/sec ²
δ	control input, in.
$\theta, \dot{\theta}$	pitch angle, rad; rate perturbations, rad/sec
τ	time delay, sec
$\phi, \dot{\phi}$	roll angle, rad; rate perturbations, rad/sec
Ω	main-rotor angular speed, rad/sec
ω	frequency, rad/sec

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Table 1. System Stability Derivatives

Derivative	Param. value	CR bound	C.R., %	Insens. %
X_u	-0.02000 ^a	--	--	--
X_w	0.000 ^b	--	--	--
X_q	0.000 ^b	--	--	--
X_v	0.000 ^b	--	--	--
X_p	0.6849	0.05632	8.224	3.489
X_r	0.000 ^b	--	--	--
Z_u	0.000 ^b	--	--	--
Z_q	0.000 ^b	--	--	--
Z_v	0.000 ^b	--	--	--
Z_p	0.000 ^b	--	--	--
Z_r	0.000 ^b	--	--	--
M_{apz}	-13.00	3.933	30.26	2.055
M_u	8.443E-04	1.904E-04	22.55	7.416
M_w	-5.142E-03	5.666E-04	11.02	4.047
M_q	-0.4192	0.03970	9.469	3.459
M_v	7.103E-03	5.803E-04	8.170	2.635
M_p	-0.2272	0.02165	9.531	3.112
M_r	-0.090000	--	--	--
Y_u	0.000 ^b	--	--	--
Y_w	0.000 ^b	--	--	--
Y_q	0.000 ^b	--	--	--
Y_v	-0.2788	0.01587	5.691	2.309
Y_p	-1.560	0.1304	8.356	3.356
Y_r	0.000 ^b	--	--	--
L_u	0.000 ^b	--	--	--
L_w	0.000 ^b	--	--	--
L_q	1.040 ^a	--	--	--
L_v	-4.247E-03	4.216E-04	9.927	3.906
L_p	-1.828	0.07974	4.361	1.104
L_r	0.000 ^b	--	--	--
N_u	0.000 ^b	--	--	--
N_w	0.000 ^b	--	--	--
N_q	0.000 ^b	--	--	--
N_v	3.008E-03	4.179E-04	13.89	4.724
N_p	-0.3085	0.02508	8.131	2.536
N_r	-0.2702	0.02309	8.544	3.373
Z_{wa}	-1.571	0.5730	36.48	6.225

^a Fixed value in model.^b Eliminated during model structure determination.

Table 2. System Control Stability Derivatives

Derivative	Param. value	CR bound	C.R., %	Insens. %
X_{lon}	-1.483	0.04423	2.982	1.339
X_{lat}	-0.1939	9.549E-03	4.926	2.271
X_{ped}	0.000	--	--	--
X_{col}	0.8355	0.02896	3.466	1.643
Z_{lon}	0.000 ^a	--	--	--
Z_{lat}	0.000 ^a	--	--	--
Z_{ped}	0.000 ^a	--	--	--
Z_{tht}	-14.62	2.090	14.29	3.432
M_{lon}	0.2353	7.660E-03	3.255	1.356
M_{lat}	0.05917	6.236E-03	10.54	3.876
M_{ped}	0.000 ^a	--	--	--
M_{col}	0.000 ^a	--	--	--
Y_{lon}	0.000 ^a	--	--	--
Y_{lat}	0.4958	0.02096	4.228	1.529
Y_{ped}	-2.791	0.07222	2.588	1.235
Y_{col}	-0.8557	0.04175	4.880	2.436
L_{lon}	-0.1042 ^b	--	--	--
L_{lat}	0.8341	0.02816	3.377	0.8260
L_{ped}	-0.4008	0.01407	3.510	1.542
L_{col}	0.000 ^a	--	--	--
N_{lon}	0.000 ^a	--	--	--
N_{lat}	0.1041	6.218E-03	5.975	2.205
N_{ped}	0.4943	0.02237	4.525	1.941
N_{col}	0.2662	0.01150	4.321	2.026
Z_{tzi}	-70.40	23.05	32.74	2.140
τ_{lon}	0.08830	6.499E-03	7.361	3.650
τ_{lat}	0.1206	6.560E-03	5.437	2.190
τ_{ped}	0.07951	4.843E-03	6.091	2.991
τ_{col}	0.06107	5.222E-03	8.551	3.357

^a Eliminated during model structure determination.^b Fixed value in model.

Table 3. AH-64 Hover Mathematical Model

u	-0.020	0.0	0.0	0.0	0.0	0.0	-32.2	0.0	u
v	0.0	-0.279	0.0	-1.56	0.0	0.0	0.0	32.2	v
w	0.0	0.0	-0.122	0.0	0.0	0.0	0.0	0.0	w
p	0.0	-0.00425	0.0	-1.83	1.04	0.0	0.0	0.0	p
q	0.000844	0.00710	-0.00514	-0.227	-0.419	-0.090	0.0	0.0	q
r	0.0	-0.00301	0.0	-0.309	0.0	-0.270	0.0	0.0	r
q	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	q
f	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	f
	-1.48	-0.194	0.0	0.835	0.0				
	0.0	0.496	-2.79	-0.856	0.0				
	0.0	0.0	0.0	0.0	-14.6				
	-0.104	0.834	-0.401	0.0	0.0				
	0.235	0.0592	0.0	0.0	0.0				
	0.0	0.104	0.494	0.266	0.0				
	0.0	0.0	0.0	0.0	0.0				
	0.0	0.0	0.0	0.0	0.0				

$\delta_{lon_{del}}$

$\delta_{lat_{del}}$

$\delta_{ped_{del}}$

$\delta_{col_{del}}$

$\delta_{col_{del}lead/lag}$

where

$$\delta_{lon_{del}}(s) = \exp(-0.088s)\delta_{lon}(s)$$
$$\delta_{lat_{del}}(s) = \exp(-0.121s)\delta_{lat}(s)$$
$$\delta_{ped_{del}}(s) = \exp(-0.079s)\delta_{ped}(s)$$
$$\delta_{col_{del}}(s) = \exp(-0.061s)\delta_{col}(s)$$
$$\delta_{col_{del}lead/lag}(s) = \frac{s + 4.8}{s + 12.9} \delta_{col_{del}}(s)$$

Table 4. Parametric Model of Dynamic Inflow Effect

$$\frac{w}{\delta_c} = \frac{Z_{\delta_c}(s - Z_L)}{(s + a)(s - Z_w)}$$

$$\begin{bmatrix} \dot{w} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} -a + Z_w & 1 \\ Z_w a & 0 \end{bmatrix} \begin{bmatrix} w \\ z \end{bmatrix} + \begin{bmatrix} Z_{\delta_c} \\ -Z_{\delta_c} Z_L \end{bmatrix} \delta_c$$

where in tables 1 and 2, these parameters are

$$\begin{bmatrix} \dot{w} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} M_{apz} & 1 \\ Z_{wa} & 0 \end{bmatrix} \begin{bmatrix} w \\ z \end{bmatrix} + \begin{bmatrix} Z_{tht} \\ Z_{tzt} \end{bmatrix} \delta_c$$

Z_w , a , Z_L , and Z_{δ_c} may be solved simultaneously

Table 5. Engine Mathematical Model

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} = \begin{bmatrix} -6.268 & -50.38 & 6.339 & 50.38 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ -4.672 & 198.2 & 4.672 & -198.2 & 0.00219 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -29400 & 0 & -2.288 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + \begin{bmatrix} -3.673 \\ 0 \\ 0 \\ 0 \\ 10620 \end{bmatrix} \delta_{col}$$

$$\begin{bmatrix} \Omega \\ \text{Torque} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}$$

Table 6. Identified Apache Stick Dynamics

	K_s gradient, lb/in	F_{PL} preload, lb	B_s damping, lb·sec/in	F_f friction, lb	I_s inertia, lb _m	X_{FP} free play, in
Longitudinal cyclic	1.1	1.4	0.03	0.3(0.1 ^a)	3.1(4.5 ^b)	0.0625
Lateral cyclic	0.53	1.0	0.2	0.3(0.1 ^a)	3.7(4.5 ^b)	0.0625
Pedals	0.7	3.0	0.3	1.0	26.0	0
Collective	(Friction adjusted by pilot; inertia not measured)					

$$\ddot{x} = \frac{-1}{I_s} \left[K_s x' + F_{PL} \frac{|x'|}{x'} + B_s \dot{x}' + F_f \frac{|x'|}{x'} \right]$$

$$x' = x - \frac{X_{FP}}{2} \qquad x > \frac{X_{FP}}{2}$$

$$x' = 0 \qquad -\frac{X_{FP}}{2} < x < \frac{X_{FP}}{2}$$

$$x' = x + \frac{X_{FP}}{2} \qquad x < -\frac{X_{FP}}{2}$$

^a Estimate of friction in flight.
^b Minimum inertia achievable in simulator.

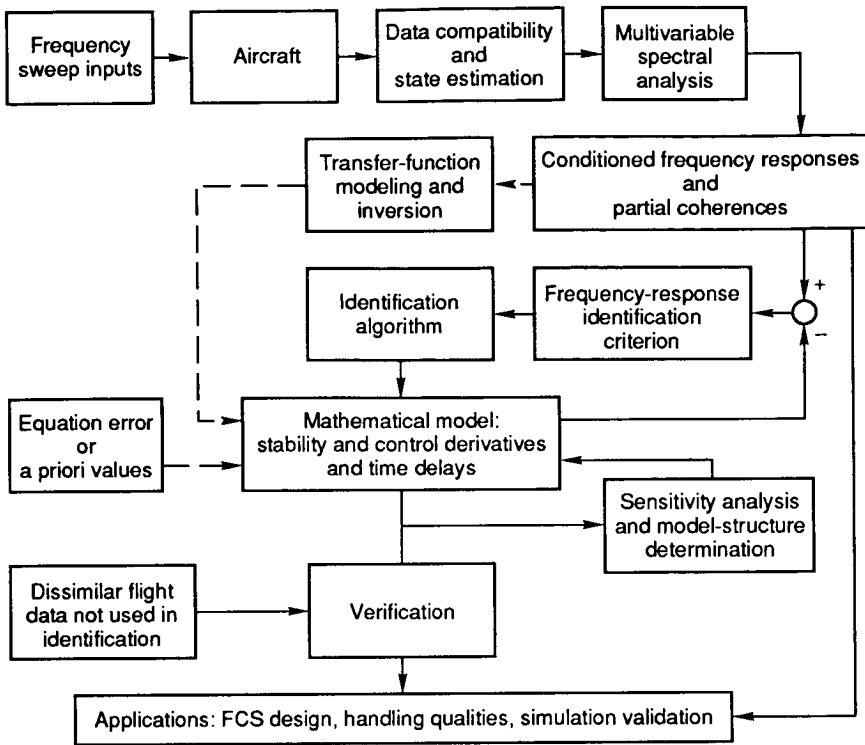


Figure 1. Identification process.

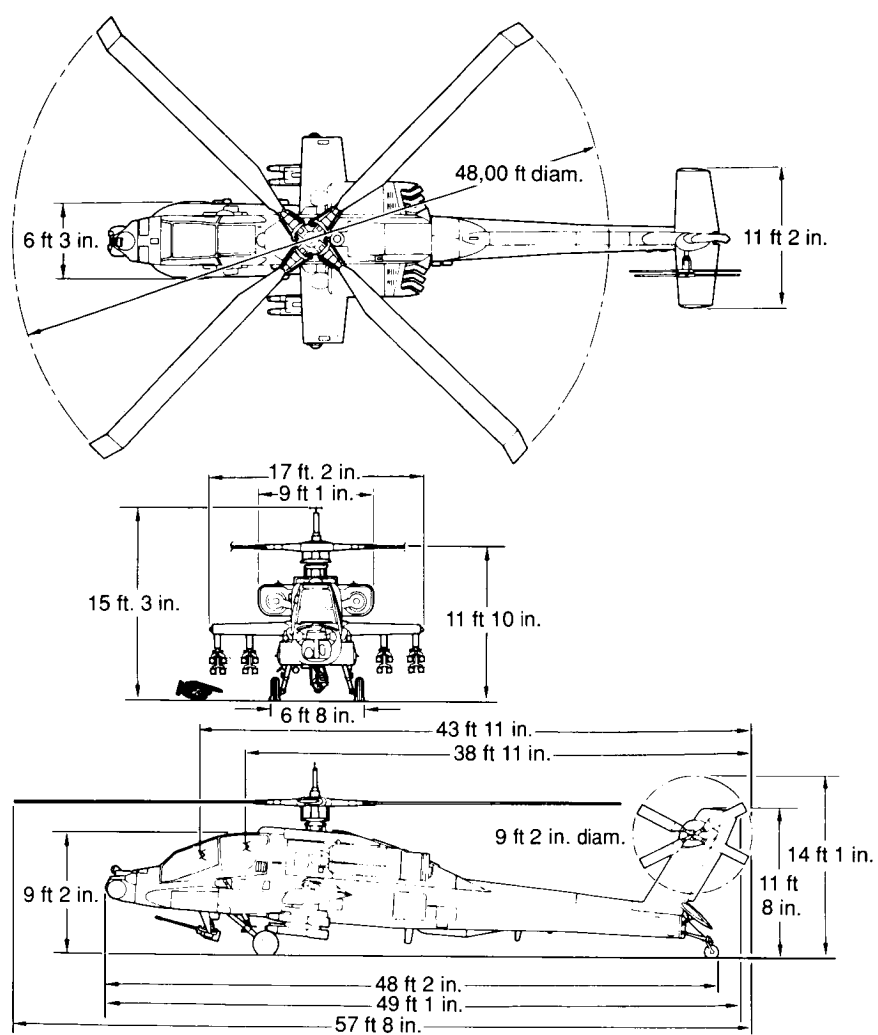


Figure 2. Principal dimensions of AH-64.

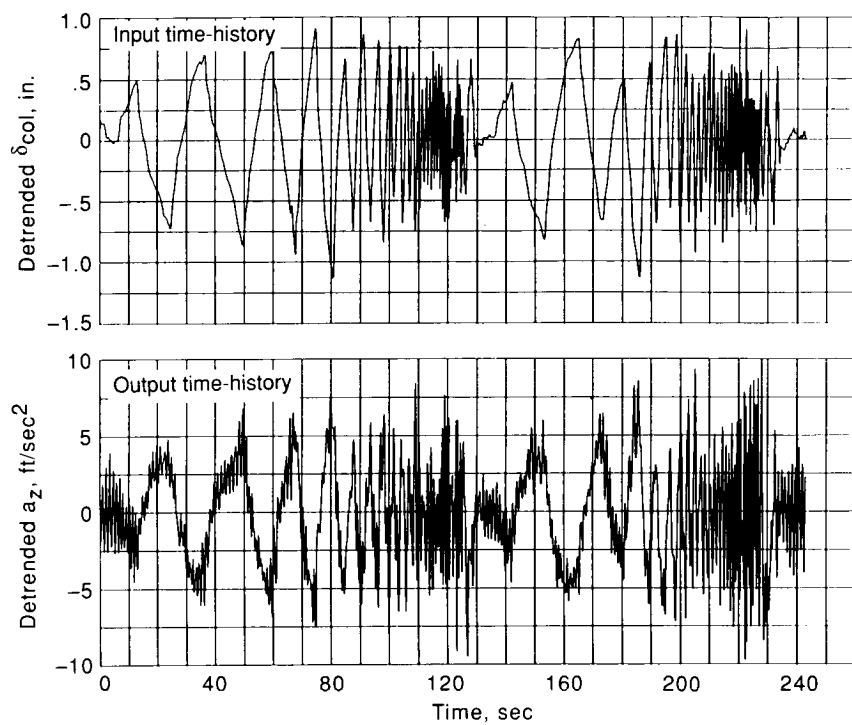


Figure 3. Example flight-test input.

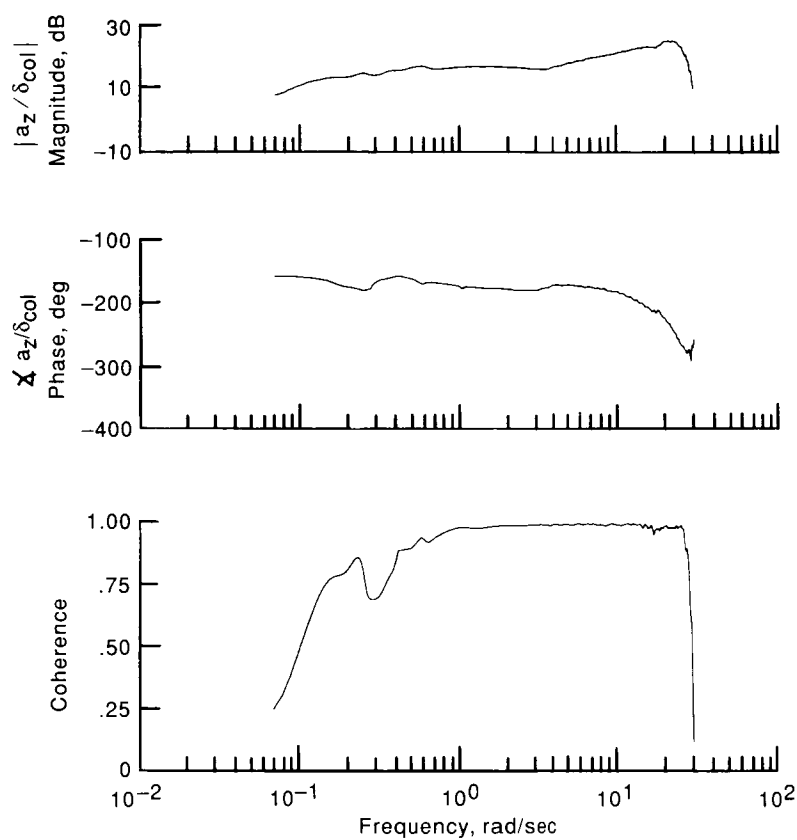


Figure 4. Vertical acceleration-to-collective frequency response.

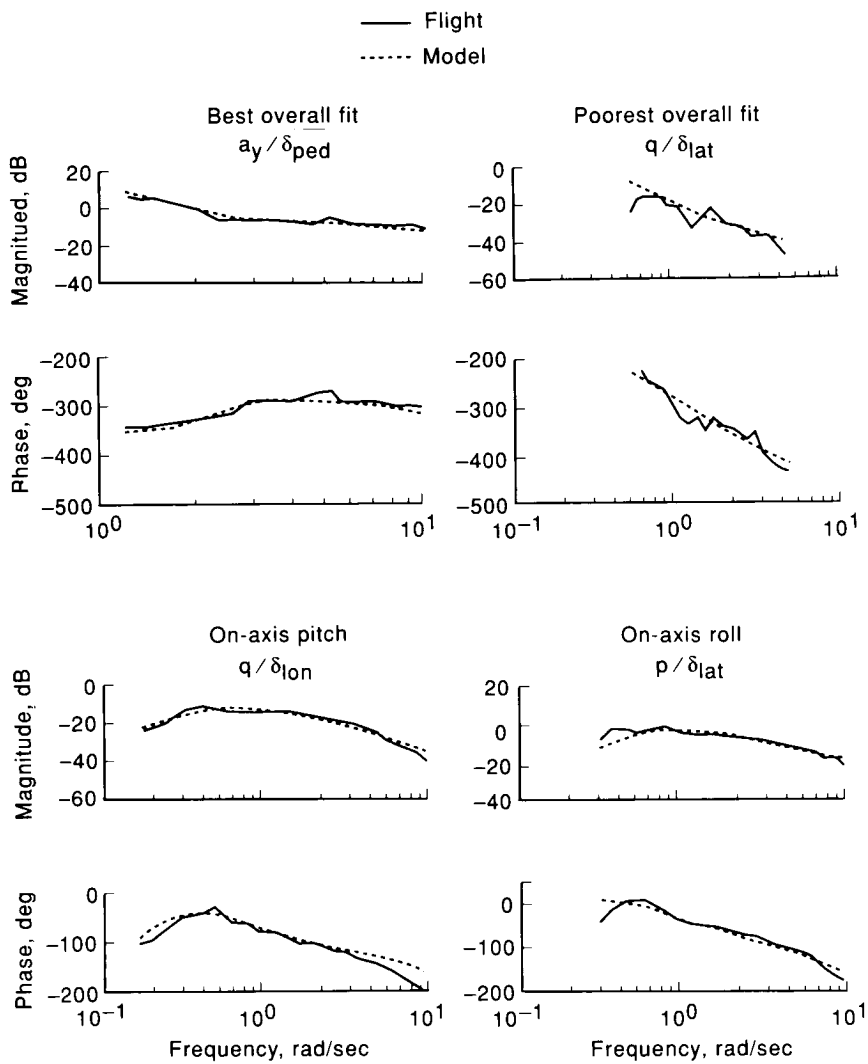


Figure 5. Example frequency-response fits.

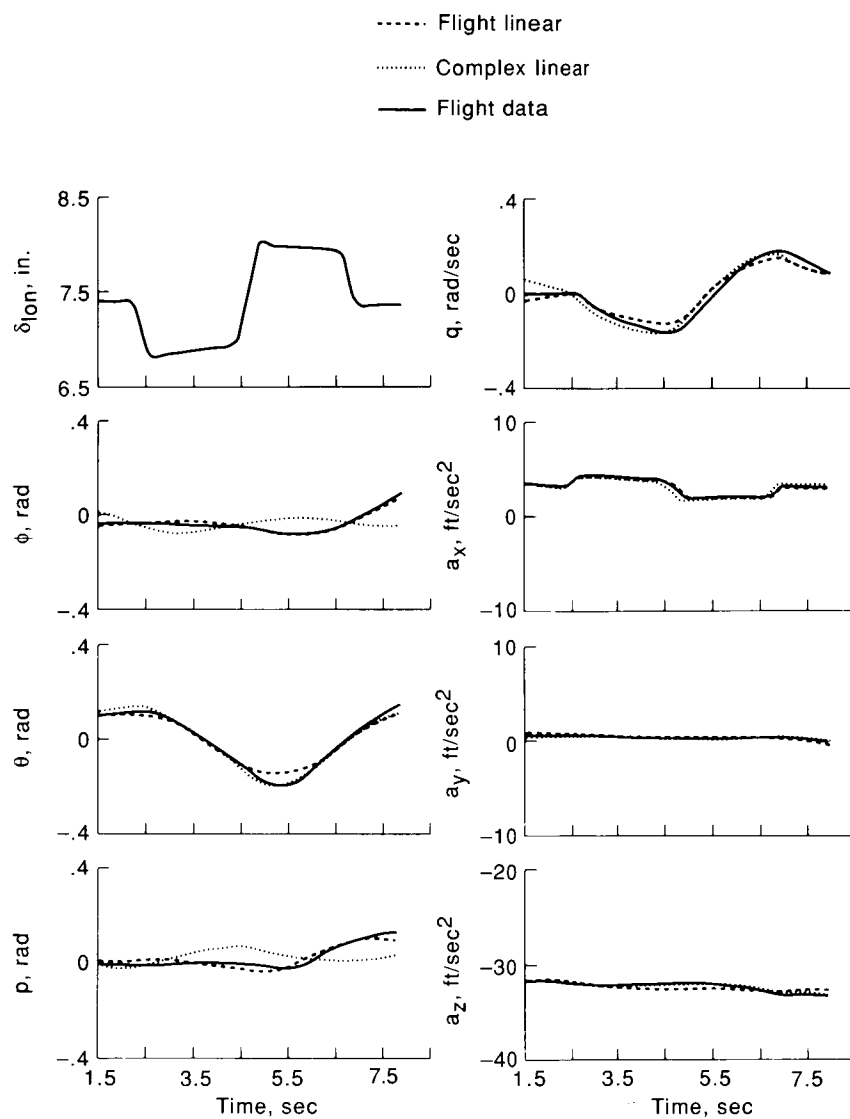


Figure 6. Flight versus two linear models for a longitudinal doublet: DASE off.

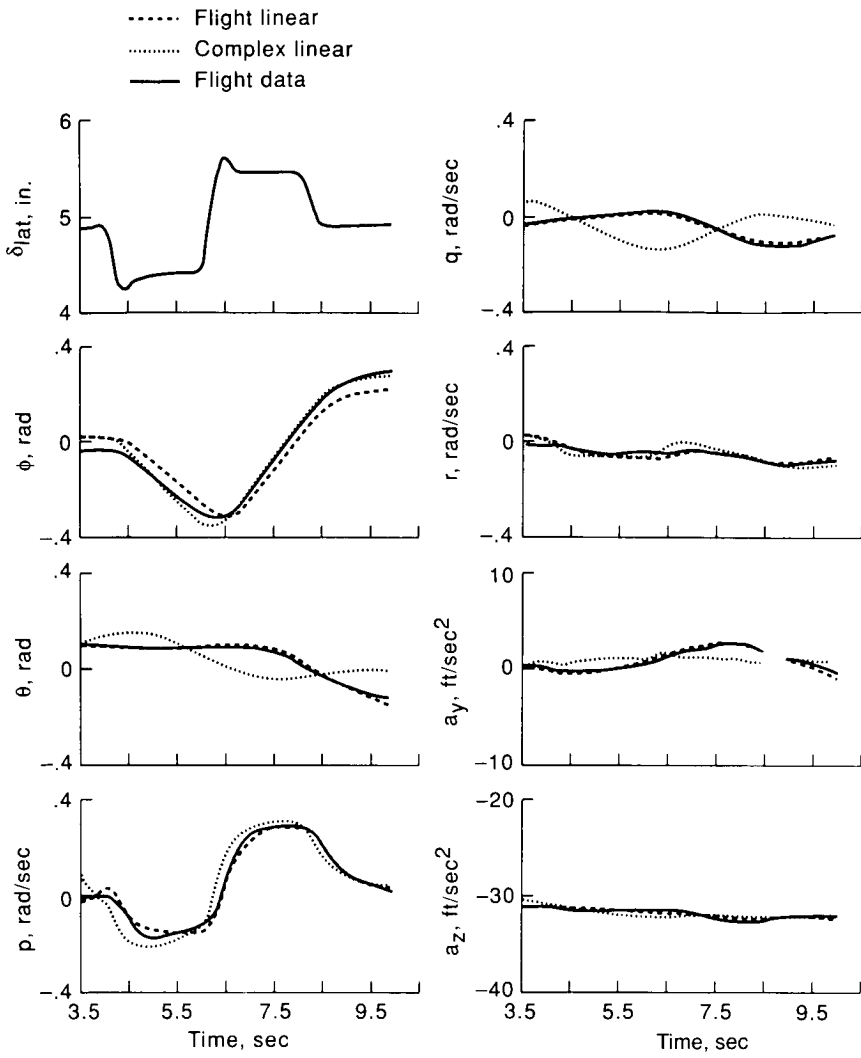


Figure 7. Flight versus two linear models for a lateral doublet: DASE off.

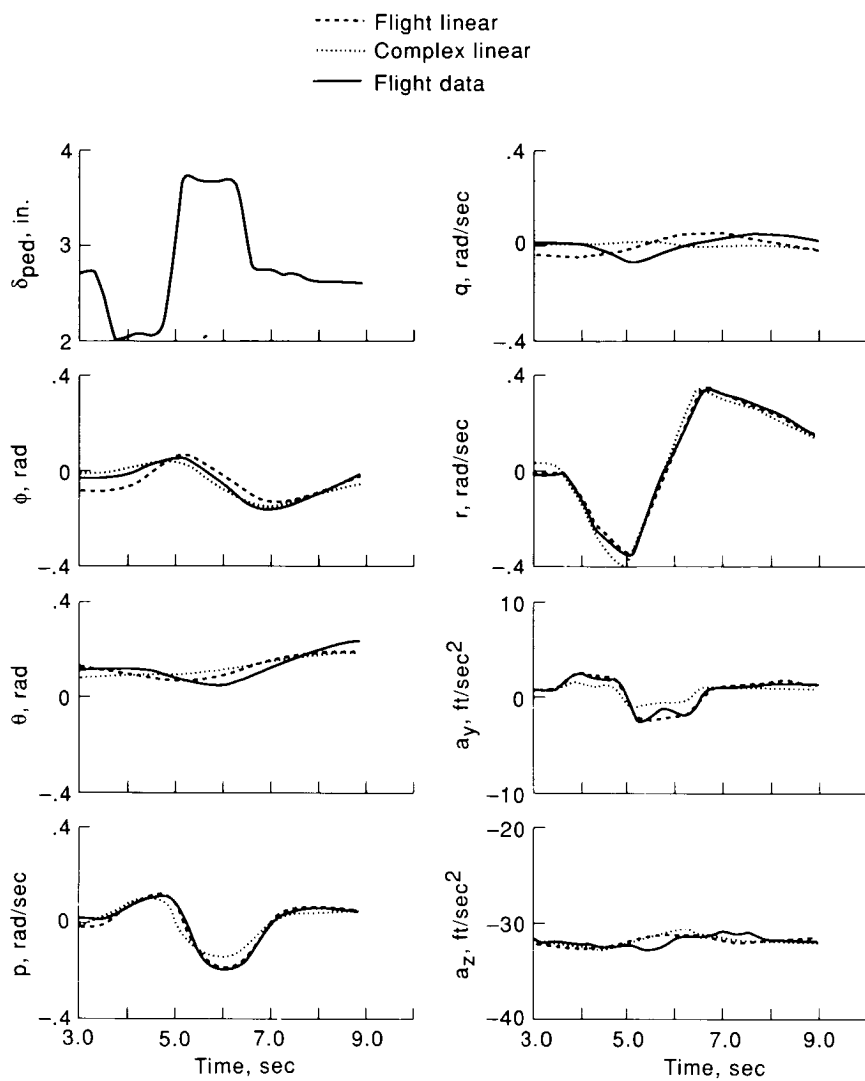


Figure 8. Flight versus two linear models for a directional doublet: DASE off.

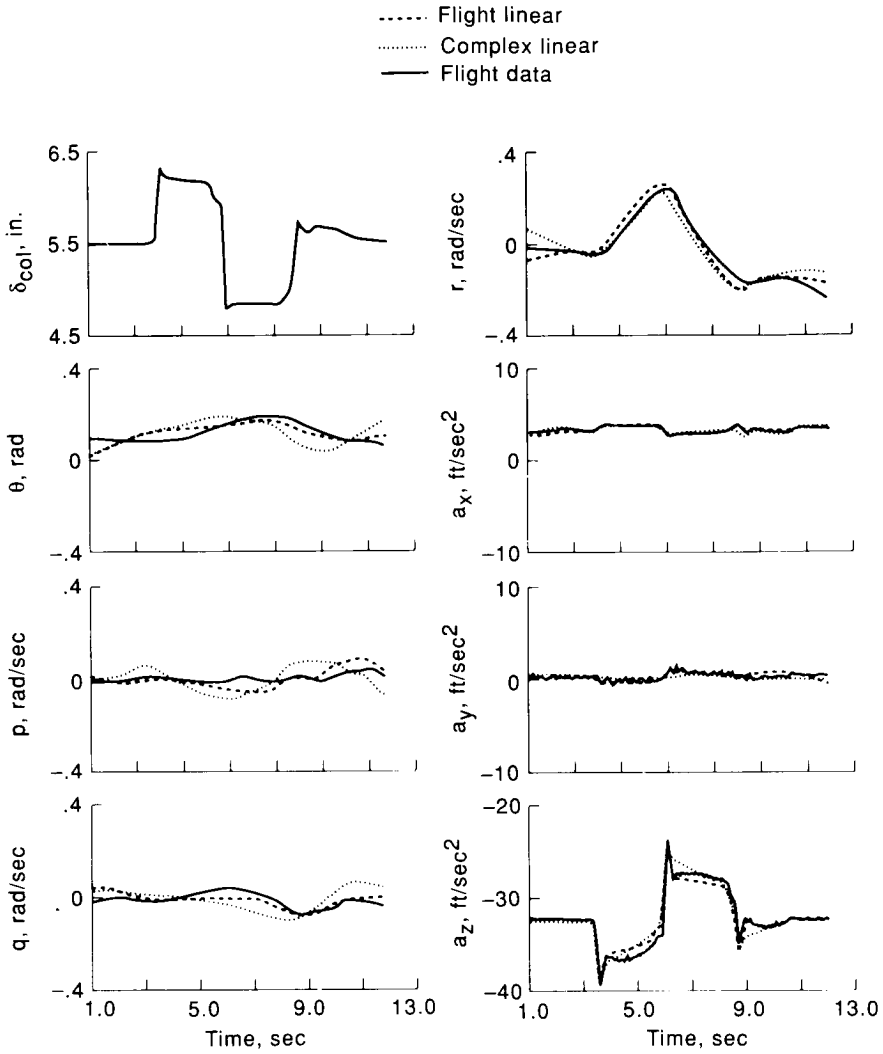


Figure 9. Flight versus two linear models for a vertical doublet: DASE off.

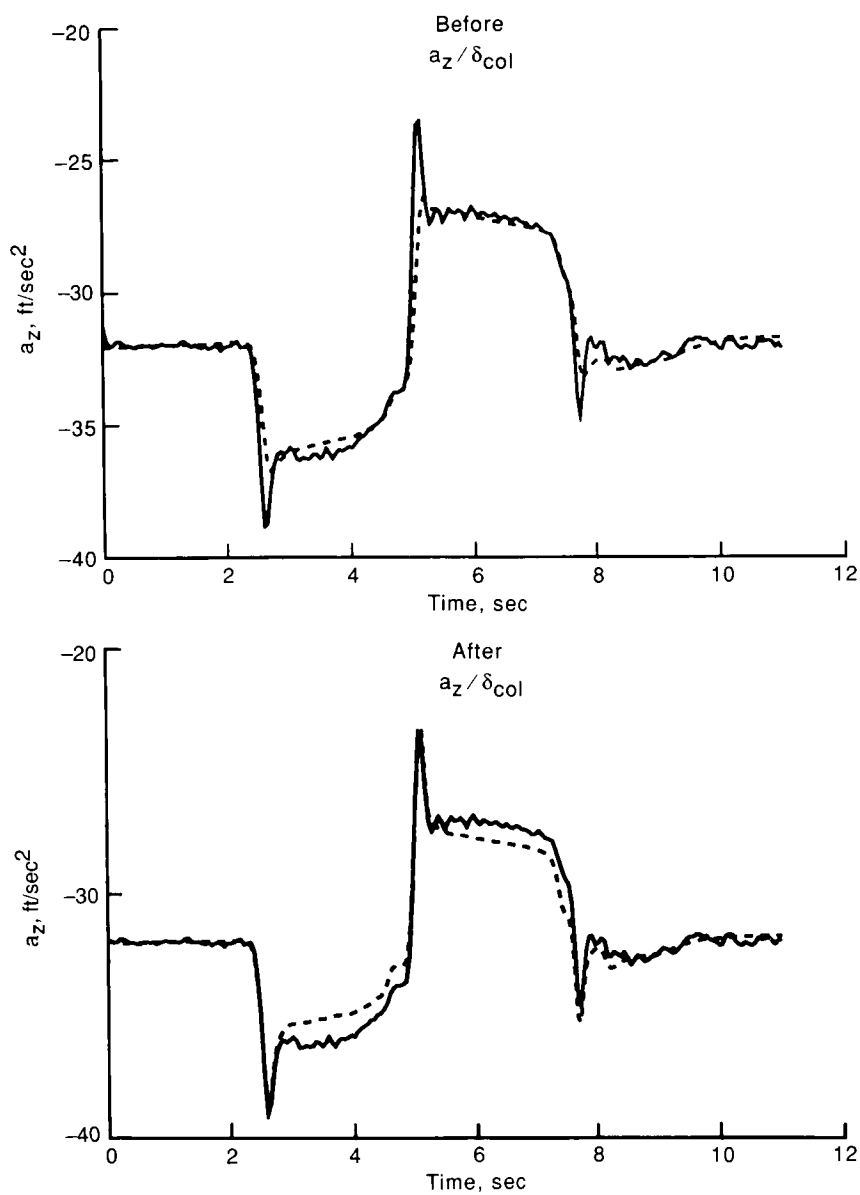


Figure 10. Effects of dynamic inflow addition.

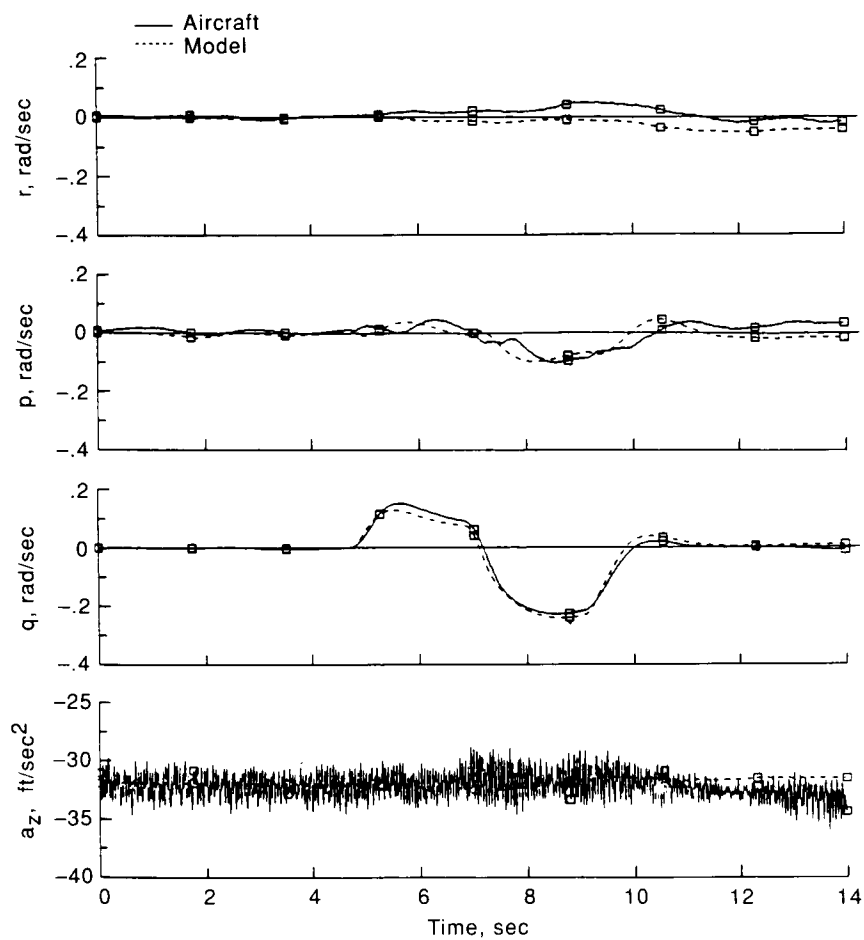


Figure 11. Longitudinal doublet: DASE on.

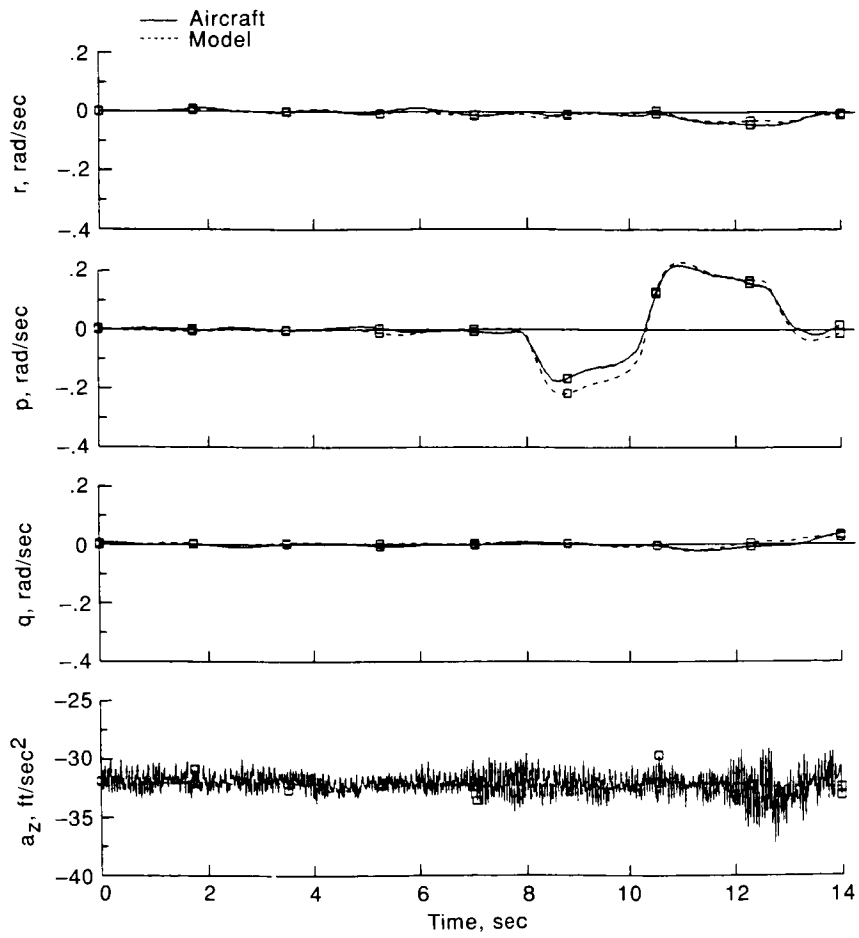


Figure 12. Lateral doublet: DASE on.

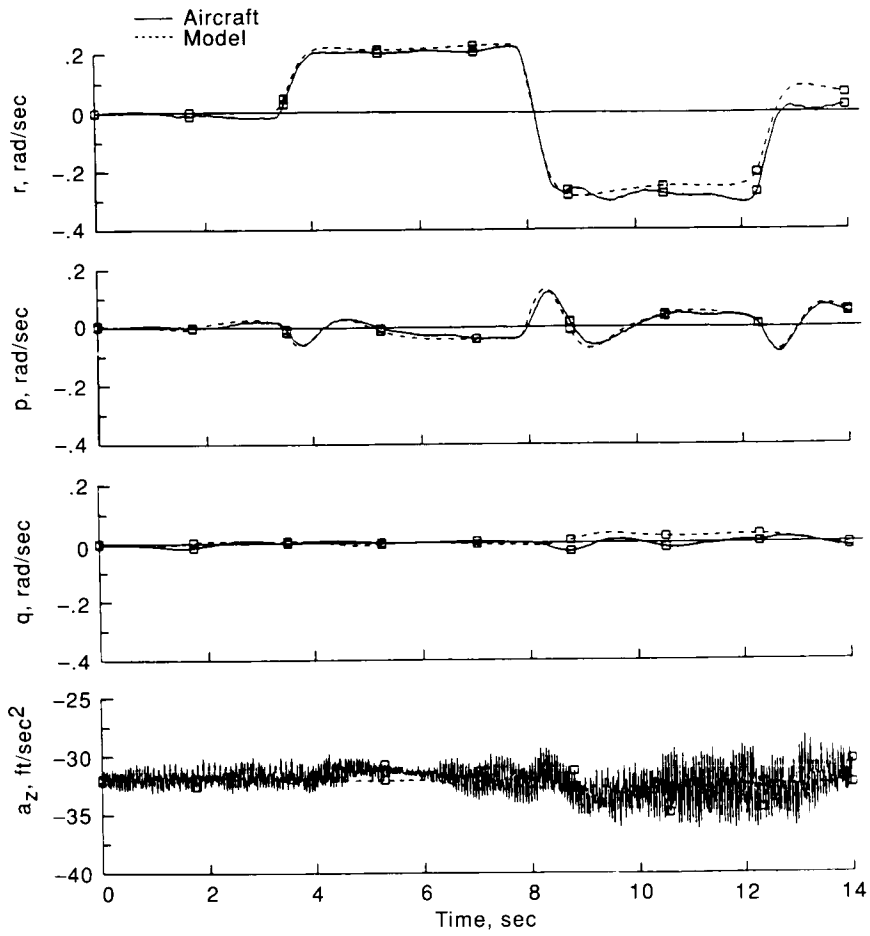


Figure 13. Directional doublet: DASE on.

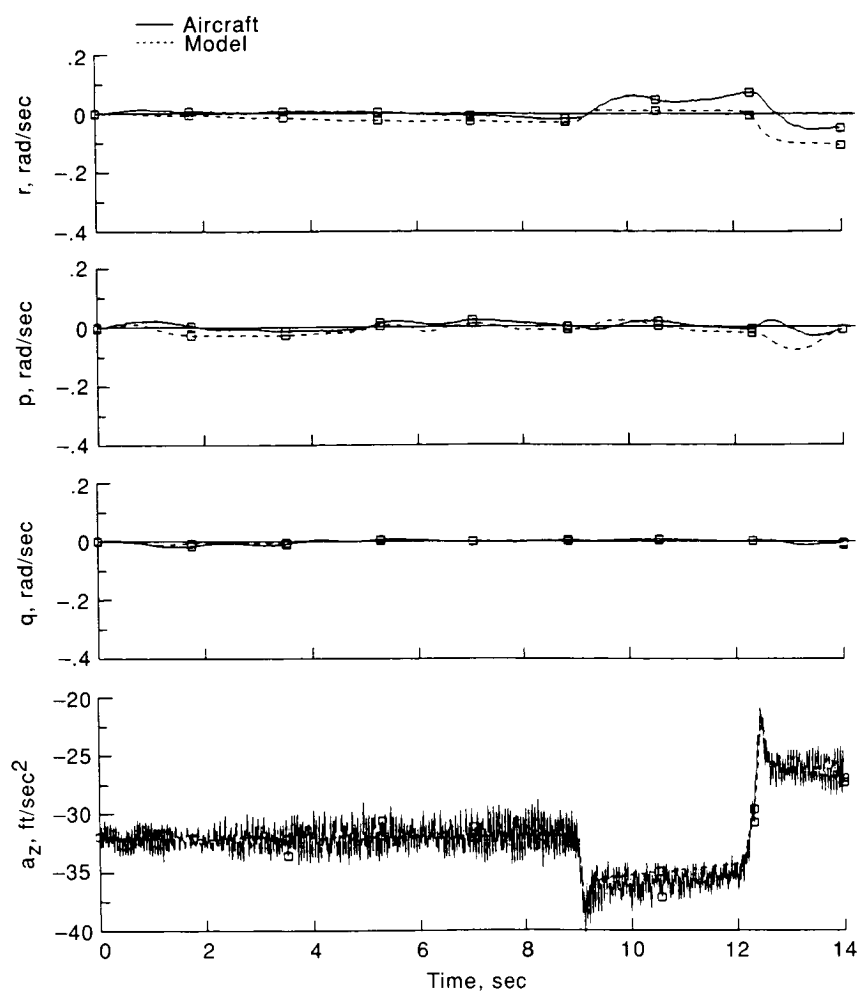


Figure 14. Vertical doublet: DASE on.

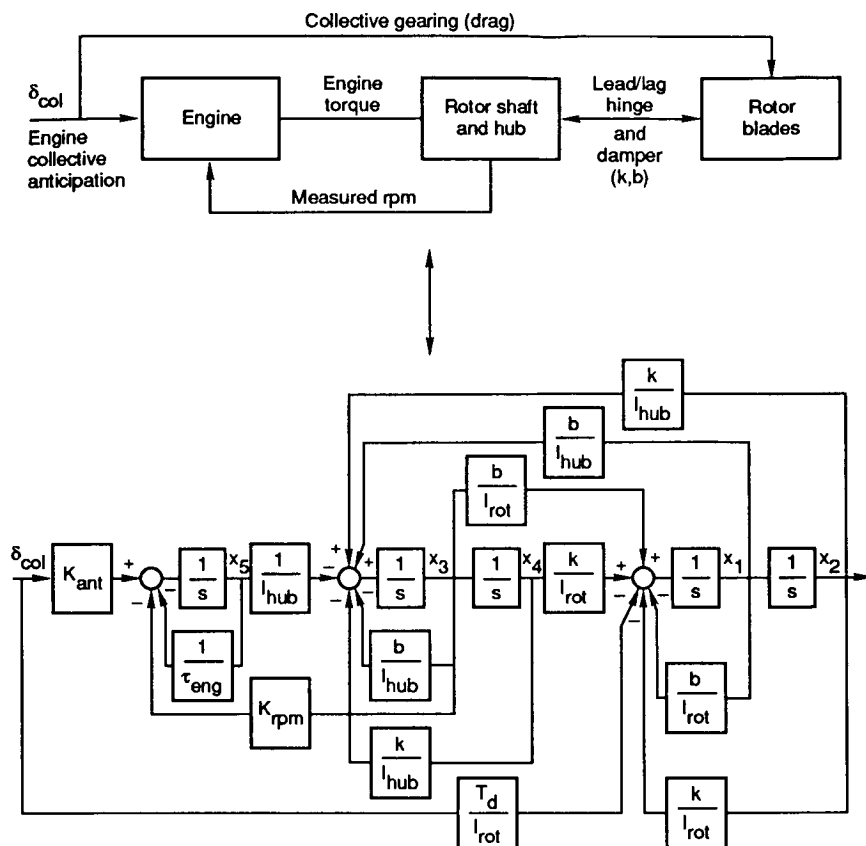


Figure 15. Engine torque/rpm model.

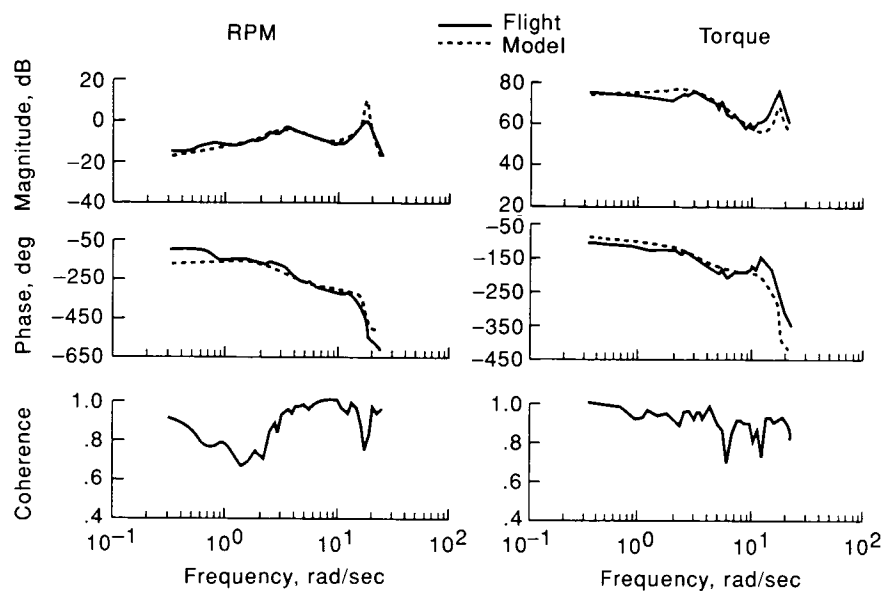


Figure 16. Flight versus model rpm and torque: frequency response.

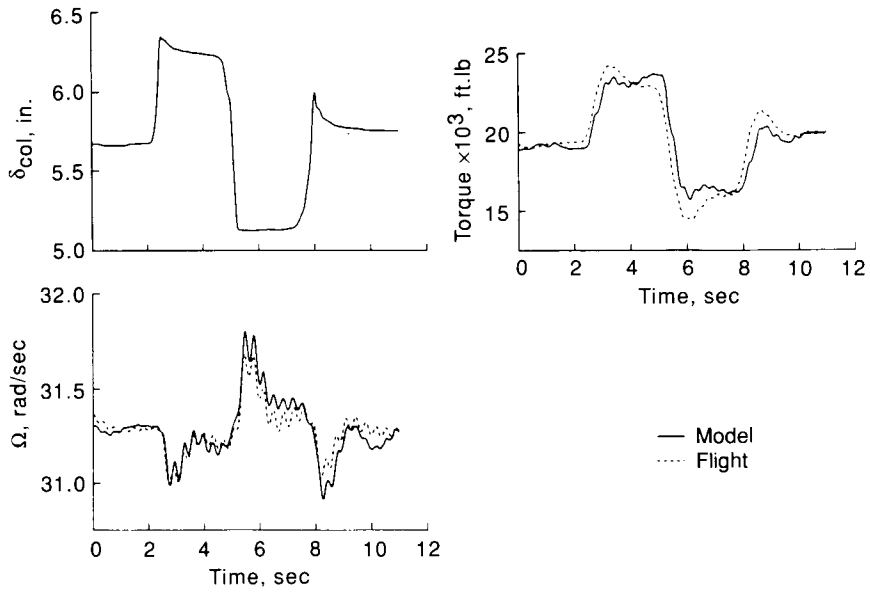


Figure 17. Flight versus model rpm and torque: time response.

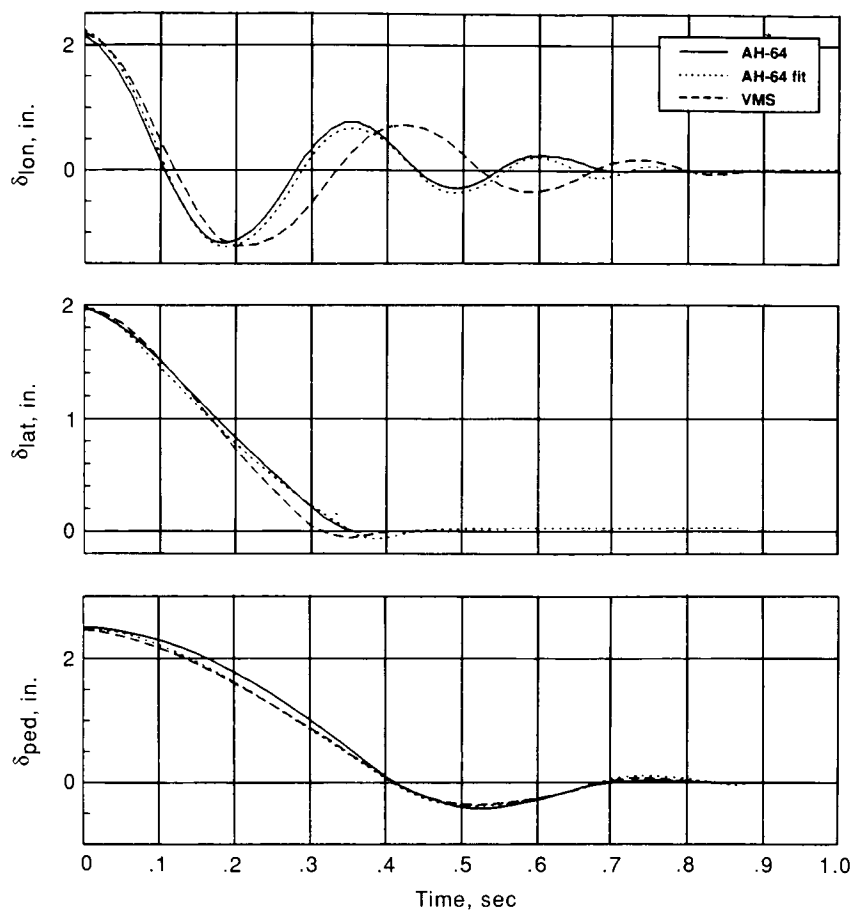


Figure 18. Aircraft versus simulation: stick response.

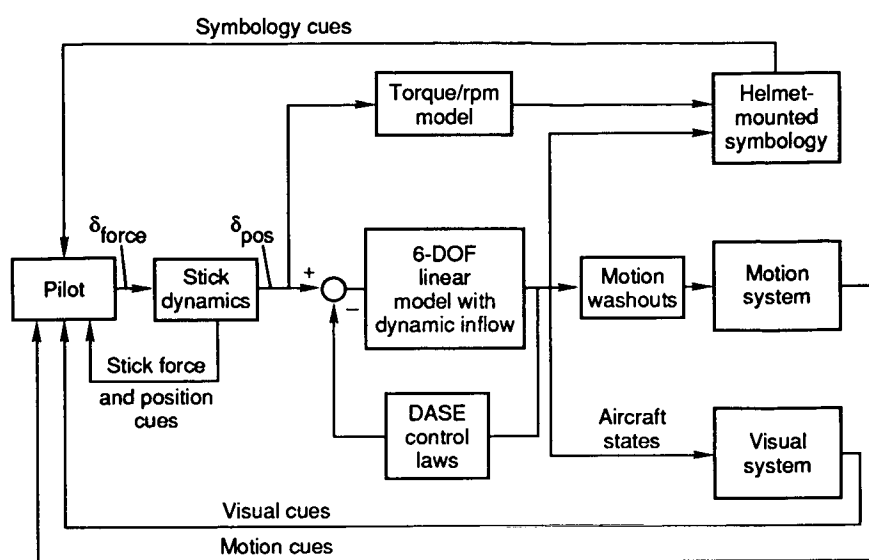
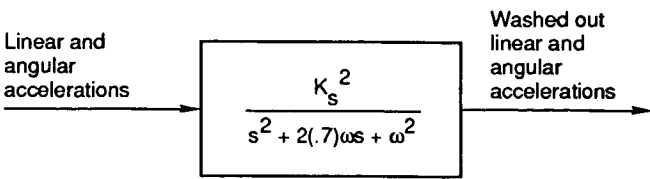
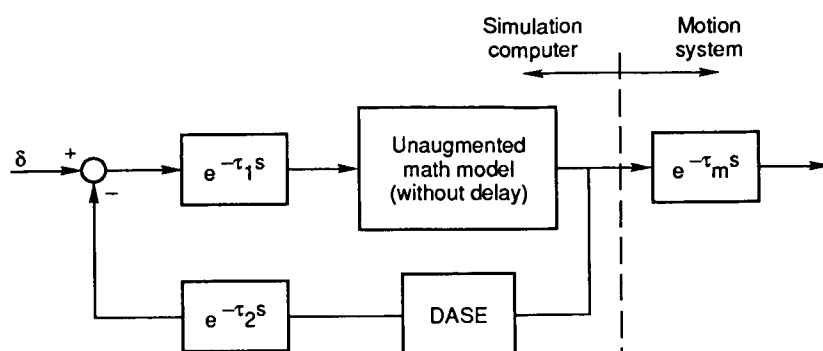


Figure 19. Simulation environment.



	K	ω , rad/sec
\dot{p}	1	0.40
\dot{q}	1	0.40
\dot{r}	1	0.40
a_x	1	2.00
a_y	1	0.60
a_z	1	0.25

Figure 20. Motion washouts.



	$\tau_1 = \tau_{\text{identified}} - \tau_m$			$\tau_2 = \min(\tau_{\text{identified}}, \tau_m)$
	msec	msec	msec	msec
Pitch	14	88	74	74
Roll	24	121	97	97
Yaw	0	79	125	79
Vertical	0	61	144	— (no vertical DASE)

Figure 21. Motion delay compensation.

10 COCKPIT MOTION IN HELICOPTER SIMULATION

Richard S. Bray*

SUMMARY

The currently proposed requirements for cockpit motion in helicopter training simulators, levels B through D, are obviously holdovers from those specified for transport aircraft simulators. Within the aviation community, controversy continues regarding the value of the motion systems that are required to meet those specifications. The intention to establish another set of specifications for helicopter simulators presents the opportunity, and the obligation, to consider the true value of such motion systems in the context of civil helicopter operations. This chapter is an attempt to put simulator cockpit motion in a realistic perspective. The limitations inherent in efforts to reproduce cockpit motions and their effects on pilot performance are described, and means of dealing with a lack of motion cues in the simulator are suggested.

INTRODUCTION

The average pilot, especially during his early exposure to the training simulator, is strong in his opinion that "Simulators don't fly like airplanes." Perhaps we could modify the above complaint to read, "Simulators don't move like airplanes." There are no hard limits to the levels of fidelity that can be attained in the dynamic modeling of the aircraft, or in reproductions of the cockpit controls, displays, and sound environment. With modern computer graphics, representations of the outside scenes can be effected with detail and with fields of view that are reasonably faithful to the in-flight task.

The remaining mode of information feedback to the pilot in his conduct of the real flight task is cockpit motion. But only a very limited portion of the flight spectrum of cockpit motions can be reproduced with a motion system of a size practical for a ground-based trainer. The following paragraphs include discussions regarding the nature of these limitations and the effects they have on pilot performance and on perceived fidelity of the simulation. Ways to improve simulator motion cost-effectiveness, and to counter the inevitable effects of motion-cue deprivation, are suggested in the concluding paragraphs.

Most of what follows is derived from my long association with National Aeronautics and Space Administration (NASA) simulators, both in their development and in their use in flying-qualities research for conventional and rotary-wing aircraft.

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MOTION CUES IN FLIGHT

Before addressing cockpit motion in the simulator context, it is appropriate to review, in an elementary way, the contributions of cockpit motion to the pilot's control of an aircraft.

Response to control: The sensory paths involved in the pilot's appreciation of the motion of his aircraft are complex. The proprioceptive cues, the pressures induced on the body by linear or angular movement of the cockpit, are primary, but closely associated with these force cues are the visual cues of cockpit structure motion relative to his head, which acts as a loosely constrained seismic mass; then, as the head moves, the vestibular organs add their contributions. As motion rates grow, visual appreciation of the aircraft's motion predominates. In his earliest experience with an aircraft, the pilot builds a subconscious mental model of responses to control inputs, and these motion feedbacks are basic to this model-building process. His trained control of the vehicle then consists in large part of precognitive inputs, that is, inputs made in predictive knowledge of the ensuing response. This action is followed by a response-feedback mode of control to adjust responses to the desired precision. It can be reasoned that in both learning and trained control, motion cues are most important when they are poorly supported by visually perceived or inferred rates, and when the control mode is characterized by high control sensitivity and tends to be oscillatory.

A signal of disturbance: Cockpit motion is the earliest annunciation to the pilot of forces applied to the aircraft that are not initiated by his control inputs. The obvious example is the aircraft's attitude and path response to atmospheric turbulence. Motion cues are the motivation for the pilot's initial control response to stabilize the aircraft against the disturbances. Attitude-rate and attitude changes induced by turbulence are strongly indicated visually, either in the outside view or on cockpit instruments; however, path perturbations are not nearly as obvious. Path stabilization in the short term relies very much on the pilot's trained ability to null the linear acceleration disturbance. An example is seen in his response to an encounter with a large up-gust early in the landing approach. The aircraft tends to heave upward and pitch down. Instinctively, the pilot of the conventional aircraft delays restoring pitch to its initial condition; in fact, he might even push the nose down farther to minimize the path disturbance. His total response is shaped by the sensed vertical acceleration, for he is not likely to have immediate visual cues of the flight-path disturbance. Only later might he sense whether his response was sufficient. If there were no vertical acceleration accompanying the downward pitch, his normal reaction would be to pull the nose back up. Other examples in this category of disturbances might be those arising from engine or control-system malfunctions.

Beyond the attitude and path disturbances that turbulence induces, it can, in its more violent forms, produce a motion environment in the cockpit, a severe jostle, that can interfere with flight management by making the reading and the setting of instruments difficult.

Annunciation of aircraft state: Another category of cockpit motion confirms specific events or announces aircraft configurations or states. In simulations of conven-

tional aircraft, examples are the jolts of main-gear and nose-gear touchdown, or the airframe vibrations resulting from stall or overspeed into Mach buffet. Flap, spoiler, and reverser deployments are all sources of distinctive vibrations sensed in the cockpit. The helicopter pilot experiences a unique set of cockpit vibration cues — those related to the speed of the rotor, the load on the rotor, and his translational velocity — that provide reinforcement of his visual cues regarding the status of his aircraft.

MOTION CUES IN THE SIMULATOR

Many flight-simulation experiments have confirmed that motion cueing usually contributes to the ease and precision of control. These results offer some indication of the level of motion fidelity (simulator motion relative to flight motion) that is required to allow the pilot to easily transfer his flight skills to the simulator. Following are discussions of the limited motion fidelity that can be attained with a conventional training-simulator motion system, and considerations of the consequences of the limitations.

The current "high-end" motion system: For the past two decades, the simulator motion system of choice has been the six-actuator "synergistic" system originally created by the Franklin Institute. In this efficient system, the actuators are the only structural elements between the base and the cab, and they can produce perturbations in all six degrees of motion freedom. Very real technical reasons, as well as housing volume, limit the extension of the actuators to about 6 feet; thus, the linear excursion envelope of the simulator is roughly described as a sphere 6 feet in diameter. Pitch and roll excursions approaching those of normal transport-aircraft flight maneuvers can be generated. The dynamic response and smoothness of the newer systems are very good; lag/delay times less than 100 msec are demonstrated, and vibration frequencies to 10 Hz or higher can be achieved.

Simulator motion algorithms: Constraining the computed accelerations of the simulated aircraft in order to keep simulator cockpit excursions within the envelope described above can involve sophisticated algorithms, but a consideration of some of the simpler processes can be helpful in describing what motion cues the device can provide. Linear accelerations or angular rates must be high-pass filtered (washed out) to limit the corresponding excursion, and direct gain attenuation of the acceleration/rate can be applied. Pitch and roll of the cab in emulation of corresponding aircraft motion must be constrained in order that the resulting "tilt" not present unacceptably large and inappropriate sensations of longitudinal or lateral acceleration to the pilot. Roll and pitch can be dealt with by attenuation only, since these excursions are limited in the flight case, but the necessary attenuation values must be of the order of 0.25. In flight, yaw is not constrained, so washout as well as some attenuation must be applied.

The three linear modes have individual characteristics that must be considered separately. Vertical acceleration is a predominating linear motion cue in flight. The 3 to 5 feet of vertical motion capability in the simulator is inadequate for the presentation of the maneuvering vertical-acceleration spectrum, which extends from 0.5 to 5.0 rad/sec. Even with the computed acceleration attenuated to one-half, the simulator cannot present

reasonably phased representations below about 5 rad/sec. Experiments in the Ames Vertical Motion Simulator (VMS) facility, which has very large vertical and lateral excursion capability, have shown that phase accuracy (lead less than 30°) at or below 1 rad/sec is required to enable flight-like precision of longitudinal path, or height-rate, control. Even for the modest vertical maneuvering of landing approach, a simulator vertical envelope of 20 to 30 feet is required to provide this fidelity of motion.

Lateral accelerations sensed by the pilot in flight are more amenable to reproduction: they are, in general, small, with a normal mean of zero. Since the cockpit is usually well forward of the yaw axis, there is a strong in-phase lateral acceleration component associated with yawing acceleration; this lateral component is important to directional stabilization in conjunction with visual cues of heading-rate. Recent experiments at Ames have confirmed that this linear-motion component is more important to yaw control in hover than is the rotational-motion cue. If, in the aircraft simulated, the pilot is not close to the roll axis, there is yet another component in the total lateral acceleration. Again at Ames, experiments have shown the importance of correctly representing the position of the roll axis. In most helicopters, the pilot is close to the roll axis, but the issue is made more important by the fact that high roll accelerations are characteristic of helicopter flight. Sensed steady-state or low-frequency lateral forces on the pilot, typically produced by sideslip, can be reproduced by tilting the cab, but great care must be taken to avoid sensory confusion that might result from any false roll motion involved in achieving the tilt.

Longitudinal accelerations sensed by the pilot in flight are seldom part of a high-frequency control loop. In the conventional aircraft, they are characterized by step changes associated with thrust or braking. In this mode, our simulator can illustrate the situation with pitch; again, however, false angular rates must be considered. In general, when this "tilt" method of providing linear acceleration cues is used, a considerable lag must be introduced in order to keep the induced angular rates low. In the helicopter, sensed longitudinal acceleration is primarily associated with drag, and is not subject to step or high-frequency changes. The main concern in the helicopter simulator is the production of false longitudinal acceleration cues; these false cues occur if large cockpit attitude changes are introduced in the simulation of the large pitch-attitude changes that are associated with quick-start, quick-stop maneuvers.

Although attenuation may be useful in constraining the linear modes at maneuvering frequencies, it is not appropriate for the accelerations produced by turbulence, touchdown, or airframe vibrations. To be "environmentally" useful, the high-frequency components caused by turbulence and by the other disturbances should and can be presented at near full gain.

The helicopter as a special case: The above discussion is appropriate for the large fixed-wing aircraft and helicopters; however, since helicopter simulator motion requirements are being considered from the perspective of years of fixed-wing trainer experience, perhaps a few more words about the significant differences are in order. The helicopter simulator is emulating a smaller, more agile aircraft with higher control sensitivities, lower stability levels, and control coupling across stability axes. Because the

vehicle, in a sense, hangs from its rotor, relatively low levels of body-axes longitudinal and lateral accelerations are generated. At low speeds and at hover, height-rate control is even more dependent on motion feedback because, unlike the conventional aircraft, it is independent of pitch attitude, and is characterized by low rate damping. A slightly wider range of helpful motion cues might be provided in the helicopter simulator simply because the maneuvering frequencies, and thus short-term accelerations, are higher in helicopter maneuvering, resulting in more cockpit motion above the pilot's sensory threshold.

In summarizing the motion system's capability to reproduce the sensations of flight, it can be said that it fails to produce many of the cues that the pilot normally uses in his "short period" control of the aircraft. It can, however, produce useful reproductions of cockpit vibratory modes and low-frequency/steady-state longitudinal and lateral acceleration.

EFFECTS OF MOTION-CUE DEPRIVATION

The roles that motion cueing play in the pilot's control of his aircraft have been reviewed, and it has been noted that severe attenuation of important cues must be accepted, even with a large expensive motion system. What effect does this have on the pilot's performance and on his sense of simulator fidelity? And to what extent do these limitations interfere with the intended use of the simulator?

Effects on basic flight control: The pilot's initial level of control and his perception of simulator fidelity will be most influenced by perceived responses to control inputs, that is, to cues in the maneuvering spectrum. The popular trainer motion system can reproduce a fraction of the angular accelerations and related linear accelerations of flight, enough, at least, to provide some relative motion between the cab and the pilot's head. This relative motion will be missing entirely in the fixed-base cockpit. The discussion here will concentrate primarily on height or flight-path control, the mode in which the acceleration cue is most severely limited, and, both in flight and in the simulator, most poorly supported by visual information.

The first efforts of even the experienced helicopter pilot to control height in the simulator entail a very high workload. Lift-off is likely to be followed by a collective overcontrolling and residual oscillatory tendencies. Translational velocity control is compromised to some extent by the workload demands of the unrealistically difficult height-control task in the simulator. If he has flown the aircraft being simulated, his expectations are particularly abused, and he will have an immediate negative view of the fidelity of the simulation. The pilot has brought his flight mode of control to the simulator, and the lack of meaningful vertical-motion cues violates his mental response model. He is part of a servo system in which the innermost stabilizing loop has been removed. Very rarely will this pilot relate his problems to diminished cockpit motion cues, for the use of these cues is a subconscious process. He is inclined to explain his difficulties as being a result of visual cue deficiencies and poor modeling of the vertical damping in the simulated aircraft. As far as the pilot is concerned, he is left with the task of "learning to fly the simulator."

Given some hours to practice, he will learn to fly the simulator. Actually, he reestablishes a new mental model, and a new set of gains in the remaining feedbacks, which are visual cues and collective position. Unfortunately, this new model construct must be accomplished in the absence of meaningful motion cues, and thus becomes a lengthened process. The pilot must be discouraged from seeking compensating information from cockpit instruments, for this procedure will only delay his effective use of the simulated outside scene. His simulator performance level will seldom reach that of his flight performance, but it will be adequate for the purposes of the training or checking exercise. What is important is that he, and the instructor pilot, judge his performance adequate, and that the workload approach a flight-like level. As his performance and comfort levels improve, so does his opinion of the simulation. Among pilots, there is significant variation in the time required for this simulator adaptation, and a minority are left with a continuing level of frustration and complaint.

Transfer of skills to and from flight: Perhaps the quickest way to put the effects of motion-cue deprivation in perspective is to cite the following observations: The pilot's initial reaction to a simulation of an aircraft with which he is familiar is usually negative, and his early performance in the simulator will be poor. On the other hand, the pilot who is well familiarized with the simulation, but who has no flight time in the aircraft, is likely to find his first flight experience very comfortable, and he will consider the simulation to be a good representation of the aircraft. In the first case, the pilot finds familiar feedbacks missing, which seriously reduces the stability of his control loop. In the second, feedbacks have been added that can be integrated to improve an already satisfactory level of performance.

The above scenarios would be appropriate for the case of a fixed-cockpit simulator, as well as one equipped with a conventional motion system. It is probable that motion-system cueing accelerates the adaptation process by offering at least some support in attitude control.

Effects on disturbance cueing: As mentioned earlier, the present trainer motion system is quite capable of presenting high-frequency motions very effectively. It can reproduce the jostle of severe turbulence, but not the lower frequencies of the disturbance that in flight inspire the initial maneuvering responses. All turbulence models become "cobblestone" turbulence. In the absence of vertical motion at maneuvering frequencies, recognition of flight-path disturbances is severely delayed. In a fixed-cockpit simulator, the same turbulence model presents even a greater, more unrealistic task to the pilot. As indicated earlier, jolts and vibrations indicative of aircraft states can be reproduced by motion systems of very modest envelope.

CAN WE CHALLENGE THE SIX-DEGREE-OF-FREEDOM MOTION REQUIREMENTS?

Considering the operating costs of a large jet transport aircraft, the losses incurred if it is taken out of revenue-producing service for training purposes, and the potential efficiency of utilizing its simulator, it is not difficult to rationalize the expenditure of \$6 million to

\$12 million for a single level C or D simulator installation. In the case of helicopter operations, such expenditures are much harder to rationalize, and it becomes obvious that all of the technology factors influencing cost-effectiveness should be examined. Cockpit controls and displays, as well as systems and aircraft performance, can and should be accurately reproduced, and the costs involved in these elements will be subject to relatively small and systematic reductions as computer costs decline. Significant cost reductions should be sought in the areas of visual and motion cueing, and regulatory standards should reflect only those simulator capabilities that have been shown to be necessary. The following paragraphs express my views regarding actions that might be taken to (1) reduce the costs of providing cockpit motion in the simulator and (2) increase the efficiency of the helicopter training simulator.

The benefits of motion: In light of the earlier discussions, what can we say regarding the value of six-degree-of-freedom (DOF) motion in the helicopter training simulator? In terms of helpful motion cueing, it might offer a bit more in the helicopter simulator than it does in the transport aircraft simulator, because control sensitivities are higher and stability levels are lower in helicopters. Attempts have been made to obtain objective measures of the contribution that cockpit motion can make to the effective use of both transport and helicopter simulators. These are very difficult experiments, and, in general, the results have shown little measurable contribution in terms of pilot performance and learning. However, on a psychological level, cockpit motion provided by the newer motion systems is well accepted, and expected, by trainees and instructors, and probably increases their respect for the simulator. It makes it easier for them to accept the simulation as a moving vehicle. Perhaps the motion does a little to ease the adaptation process psychologically, as well as physically.

The costs of motion: But if the benefits of 6-DOF cockpit motion are vague, its cost is not. The actuator system itself is expensive, initially and in operation. Simulator housing volume and the floor design required with the motion system add significant costs. The visual presentation system must move with the cab, and thus must survive its vibrational environment, thereby increasing its initial and maintenance costs. I cannot quote a true motion cost fraction for a level C or D simulator, but I am sure it is considerably greater than that of the motion system itself.

A less costly motion system for levels C and D: Considering the cost and ill-defined benefits of the 6-DOF motion system, what are the regulatory agency's justifications for its requirements? The proposed requirements specify no excursion envelope, and no motion-fidelity criteria other than a maximum response delay. Motion cueing of a number of airframe disturbances is specified, but all are high-frequency in nature, requiring very modest excursions of the simulator cab. A system with a motion envelope considerably smaller than those now in use should meet these requirements.

Considering that body-axis longitudinal accelerations are not important cues in helicopter flight, a longitudinal degree of motion freedom seems unnecessary. Earlier, in consideration of the significant cues that might be reproduced in the simulator, it was noted that the most valuable linear acceleration cues might be those associated with aircraft angular accelerations around axes removed from the pilot's location. This leads me

to suggest a three-actuator, 5-DOF motion system that moves the cab in limited yaw and pitch rotation about a fixed universal coupling 6-10 feet aft of the pilots' station, and that also rolls the cab. Obviously, roll would be the only uncoupled motion, but the coupling of lateral acceleration with yaw and the coupling of vertical acceleration with pitch is natural in flight, and should be acceptable in the helicopter simulator. Certainly, all of the high-frequency disturbance cues could be adequately represented. However, great cost savings cannot be claimed for such a system. The actuator costs might be halved, but housing costs would be only modestly reduced, and the motion environment of the visual presentation system would not be appreciably attenuated.

Does level B need cab motion?: It is my opinion that level B training simulators should not be burdened with a cockpit-motion requirement. Airframe vibrations and landing shocks can be represented with current "seat-shaker" technology. With the liberation of the visual presentation system from the cockpit structure, relatively inexpensive projection configurations, with wide fields of view, can be considered.

COMPENSATION FOR MOTION-CUE DEPRIVATION

The severe reduction of maneuvering motion cues in the training simulator places a very real limit on the objective fidelity of the simulation. We know exactly what the pilot is missing, but the significance of this deprivation can be assessed only by his subjective impressions and his performance. Perhaps we should use his performance, especially his early performance, compared with that in flight, as the true measure of simulator fidelity. If the pilot can, from the start, operate as he does in the aircraft and produce similar levels of performance, his subjective impressions of the fidelity of the simulator will be high, and certainly his ability to use it in the attainment of training objectives will be maximized. In the absence of important motion cues, is there any way to achieve this handling-qualities parity between simulator and flight?

In analysis and experiment, direct efforts to define the role of motion cues in pilot control have met with only moderate success. If we had a high-fidelity model of this process, we might augment the pilot's control inputs in compensation for the missing cues. It has been observed in helicopter simulations that a higher vehicle stabilization level is required in the simulator to elicit the same handling-qualities ratings given in flight. For example, an attitude-command control system in the simulator might receive the same rating as a rate-command system in flight. This suggests that the subjective fidelity of the training simulator can and should be enhanced by altering some aspects of the dynamic response of the aircraft model in order to promote a more stabilized control loop. Perhaps, to some small degree, such a process does take place in the acceptance tests of a new simulator. Since the acceptance pilot's opinion of the simulator is directly related to his perception of his performance, he will urge or demand changes (tweaks) in the model (supposedly within data uncertainties) until a combination of the changes he recommends and his accommodation to the simulator allow him to perform to his expectations. It is likely that this tweaking is not always a model-correction process but often a cue-deficiency-inspired one.

Systems Technologies Inc. has attempted to verify simulator fidelity by matching closed-loop performances. This effort might be carried on to the development of an analytical procedure that would define an altered model providing flight-like subjective sensitivity and stability in the simulator, if not a complete reproduction of the control bandwidth. Hovering-height control would be the obvious first target in an attempt to match ease of control, since the task is so much more difficult in the simulator than in the aircraft. Judicious modifications to heave damping, control power, and, perhaps, the ground-effects model might bring the workload down to appropriate levels and thereby actually increase the validity of the simulation. More sophisticated approaches would probably involve "shaping" of the pilot's control input.

A CONCLUSION AND A RECOMMENDATION

It is concluded that no hard measure of cost-effectiveness exists for the motion systems currently mandated for helicopter simulators. To burden helicopter simulators with expensive motion systems simply because the air-transport community agrees to their requirement is bureaucracy at its worst. For the helicopter, the simulator application is different, and the operational economics are different. The regulatory agency should promote investigations that define the value of various levels of cockpit motion in the training mission, and should support exploration of means by which the inevitably missing cues can be compensated. Perhaps within our down-sized military, a modern helicopter simulator could be put to use exploring these questions.

11 VISUAL SPACE PERCEPTION IN FLIGHT SIMULATORS

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Absolute realism is, and will forever remain, unattainable through simulation.

— Gullen et al., *The Computer Image Generation Applications Study*

SUMMARY

The outside visual scenes in flight simulators have become more and more sophisticated over the years, but the sophistication refers to advances in optical and computer characteristics, that is, to form rather than function, in providing a synthetic visual environment. It is our contention that the visual perceptual requirements have never been completely thought through, probably because the projected images of the world that have been presented have an inordinately strong face validity, which is to say, a superficial validity. This has been referred to as apparent realism. Our purpose herein is to discuss the visual requirements at a fairly fundamental level, because it appears that a need exists for a more veridical, or at least more functional, representation of the vertical flight environment. This is a circumstance peculiar to rotary-wing aircraft because of their unique maneuvering and operational repertoires. Some of the possible sources of visual perceptual error in the use of collimated displays are discussed, and, with perhaps a touch of analytic temerity, an analysis of the dynamic visual cues that underlie low-level flight over unfamiliar terrain is presented. Our treatment is not exhaustive, of course; it is meant, rather, to free the thinking of simulator designers from the lure of precedent as the overarching design guide and to convince them to take a fresh look at the fresh problem facing us in the coming world of vertical flight.

INTRODUCTION

There are obvious differences between the maneuvering envelopes of rotary-wing and fixed-wing aircraft. In fixed-wing aircraft, flight — and pilot vision — is primarily forward-oriented and more or less horizontal with respect to Earth's surface. In rotary-wing aircraft, flight — and pilot vision — is both forward and downward-oriented. Rotary-wing aircraft can and do fly forward, sideward, and backward, and they can change altitude while not doing any of these or while doing all of them. This extended versatility with its added degrees of freedom leads one to question the use of fixed-wing visual-scene generation techniques for rotary-wing training simulators.

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Computer-generated scenes are presented in perspective view and optically localized at infinity (or at least at a great and constant distance) on a vertically projected surface in a two-dimensional depiction of three-dimensional space; this provides a visual environment that is at best illusory. Roscoe has referred to it as "The apparent realism of the illusions created" (ref. 1). This deception has not been too disruptive for the great wealth of training that has been and is being accomplished in fixed-wing simulators, but it may well be a source of problems in rotary-wing training, particularly since the need for these pilots to make accurate size, distance, and rate judgments is so crucial to their maneuvering versatility and safe flight. Frequently mentioned complaints with simulators of rotary-wing aircraft are the lack of field of view and inadequate textural cues. It is to be noted that these complaints may really mask more fundamental inadequacies caused by the way we currently present extracockpit scenes.

In 1980, Gullen et al. made the following and still pertinent observation:

Absolute realism is, and will forever remain, unattainable through simulation. Simulation is the exact, or not so exact, antithesis of realism. A simulated object is not, nor can it ever be, the object. A photograph is considered to be the epitome of pictorial realism, yet a photograph of a real-world scene is an abstraction of that scene, just as any CIG [computer image generation] image is an abstraction of the real world it is meant to represent. With this fact in mind, it must become apparent that no CIG scene may ever become the real world. Consequently, a decision must be made as to what is adequate scene detail and what is required scene detail, since under all conditions the scene portrayed will be an abstraction. Rephrasing this concept: All CIG is abstract. A decision must be made as to what degree of abstraction is *reasonable and adequate*. There is no single answer to this question. What is reasonable and what is adequate changes with mission task and desired goal. [ref. 2]

In this chapter we review some of the basic, functional characteristics required of a visual environment in order to support human visual perception. This will be done by reference to naturalistic space perception. A later section includes an analysis of the perceptual geometry of dynamic rate, size, and distance judgments in nap-of-the-Earth and terrain-following flight even over unfamiliar terrain. It will be seen that that behavior is only secondarily dependent on the well-known "static" visual depth cues. It goes well beyond these and, through motion perception (optic flow and streaming), is able to perceive not only relative but absolute (egocentric) depth. It is hoped that this discussion will provide some insight into the functional requirements for vertical-flight simulators and that it will point out some of the differences of those requirements from those of conventional horizontal-flight simulator visual scenes.

Several terms are used to describe simulation fidelity: equipment fidelity, engineering fidelity, dynamic fidelity, and perceptual fidelity to name a few. A more useful designation is that of functional, or training, fidelity which refers to the correspondence between the behaviors required for skilled performance in the aircraft and those behaviors developed by practice in the simulator. This kind of fidelity differs from the other aforementioned fidelities: it refers to the ability of the simulator to provide training that will *transfer* to the aircraft. The other fidelities may be important, but they, alone, do not assure a high degree of training transfer. They can, at least

theoretically, be objectively measured. But the extent to which functional fidelity or training transfer can be measured — and the extent to which it *is* measured in civil simulators is practically nil — is the extent to which one measures the capability of the simulator in terms of its primary function and ultimate criterion. By default, in the absence of these tests of functional fidelity, we insist on high physical fidelities, assuming that high functional, or training, fidelity must follow. In practice it is easy and more economical to forego training studies and the assessment of functional fidelity and to take the risk of assuming a one-to-one correspondence between training efficacy and the physical fidelity of the simulator.

PERCEPTUAL FIDELITY

There are some aspects of visual simulation in which the *perceptual fidelity*, measured in terms of that most important human sensory system, vision, is not adequate. But that inadequacy has nonetheless been pretty much inconsequential in terms of *functional fidelity* for training in fixed-wing aircraft. However, this same inadequacy needs to be re-evaluated in the case of rotary-wing aircraft because of the different perceptual requirements they impose on their pilots and because of their crucial maneuvering differences.

The inadequacy derives from the use of collimated visual scenes. It has not meant much in the fixed-wing case, perhaps because the missing cues may not be that necessary for the training being given or because the trainees simply live with the situation and do not consider it that troublesome. A great deal of that kind of *dissimulation* goes on in simulations; it is part of the willingness to play the game and maximize the personal benefits of the training, which is undoubtedly a strong trainee characteristic in successful training systems.

Outside visual scenes in most current flight simulators are collimated images of a flat surface on which a computer-generated image of a three-dimensional world is represented in two-dimensional drawings. Where the ancients who instituted perspective drawing used strings stretched between points on an object and an eye-point represented by a single nail driven into a wall, we now do it with computers and then transform the "object coordinate system" to the "eye coordinate system" to produce the "pyramid of vision." Unfortunately, perceptual fidelity in terms of visual *volume* is lost in this world of "flat-landers."

The flat, two-dimensional surface is placed at or near the focal plane of a collimating optical system with the pilot's eye placed at or near the opposite focal plane. The resulting illusion created by the virtual image of the flat picture is one of infinite or great distance for all scene elements. The crucial phrase is "all scene elements." The optical message is that all distances are equal and far away. However, the conflicting message from scene perspective, motion, and other monocular cues is that distances are varying. There is no optical depth, that is, relative distances are depicted perceptively but not optically. Depth must be inferred from perspective and other monocular cues such as overlay and texture gradients. As one helicopter pilot reported in a recent magazine article, "Although the simulator is depicting a landed helicopter, the presentation leads you to think you are in a low hover." His perception was that he was too high, and this was partly a consequence of his distance above the ground being the same *optical distance* as the horizon. He did not see himself as being

quite that far away because the monocular and contextual cues and his low credulity reduced the illusion — but not completely.

In these collimated scenes the loop has been opened for binocular cues and depth — stereopsis, vergence of the eyes, and accommodation (visual focus) are open-loop because the optically mediated scene is at great optical, but not real, distance. There is no retinal disparity for stereopsis and no differing object distances to stimulate vergence and accommodation. However, the illusion is very compelling in terms of the perception of flying around in a vast and almost unrestricted area — and that may be its major strength. This dramatic optical illusion has probably had much to do with the increasing acceptance of simulators as bona fide devices in which to practice flying. It also undoubtedly has much to do with their apparent functional fidelity and our overlooking of the fact that some perceptual fidelity is lost because of the nullification of these three basic visual functions: stereopsis, vergence, and accommodation.

When we are in a simulator it is easy to dissimulate and to pretend we are flying the simulated aircraft. If the training is intense, and if we are being evaluated for our ability to handle several unpracticed emergency situations, we soon forget that it is a simulator. If we do well, we applaud the simulator for its ability to prepare us for the aircraft; if we do poorly, we say the simulator is nothing like the aircraft. Dissimulation is an important component of a successful training program.

CONSEQUENCES OF IMPERFECT FIDELITY

An observer in a helicopter research simulator found it to be dramatically obvious that the apparent size of two generic pylons placed on the ground plane for hovering maneuvers was changing. As the helicopter approached the pylons they, of course, grew in angular size, but they also *changed in phenomenal or perceived size*. There was no way to know their real size at a distance so their size was indeterminate when he got close, except that they were smaller and bigger, respectively. This is a second kind of response to the indeterminacy in spatial extent in collimated scenes. The helicopter pilot quoted above experienced and reported a distance anomaly ("... leads you to think you are in a low hover"); this observer experienced a size anomaly. These are simply two aspects of a basic, inseparable function — the perception of spatial extent, size, and distance. The distortion of spatial extent is very obvious when viewing collimated runway markings while parked at the threshold — they are huge, sprawling, and totally unrealistic in their extent.

There are practical consequences of this spatial indeterminacy. This has not been a problem in civil fixed-wing simulators because there is little or no need to precisely estimate near-distances. Also, it may not have been a problem because of the large redundancy in the cues in our visual world and the human ability to continue to successfully form veridical percepts when these cues are reduced in number and quality. There is thus little effect on functional fidelity or training effectiveness of fixed-wing training devices. That may not be true in rotary-wing training.

Size-Constancy

But why the growth in size at close distances? We may not be able to make accurate size and distance judgments because of the weakening of the size-constancy

phenomenon that is normally supported by the three missing visual functions: stereopsis, vergence, and accommodation. This nulling of a natural visual process is abetted by the fact that it is the sizes and distances of *pictures* of objects that are being estimated rather than the objects themselves. Size constancy is one of those "built-in" behavioral mechanisms that we depend on every day but that we seldom notice. When familiar objects approach or recede from us, their visual angles change drastically but their perceived sizes do not. A 6-foot person at 20 feet subtends an angle of 17° ; at a distance of 5 feet the angle is 50° , so the retinal image has increased threefold, but the person's perceived size has not changed and normally is not seen as growing larger as distance is decreased.

Fifty years ago, Holway and Boring did a study of visual size perception that has since become a classic (ref. 3). They found that size constancy broke down as certain visual cues were removed from the viewing situation. When binocular cues were removed, size constancy was weakened. When accommodation was also removed, it was further weakened; and when perspective or contextual cues to distance were also removed, the perception was almost entirely a function of the visual angle of the stimulus. That meant that as an object approached, it got phenomenally bigger and lost its cue value as having a familiar and invariant size. We have a similar situation in our simulator scenes except that we have not removed the perspective cues. The net effect is that size constancy is weakened and that approaching objects in the visual scene are perceived as constantly increasing in visual angle and phenomenal size and thus have little operational utility. The perceptual "reflex" of size constancy has been rendered useless in the shift to the law of the visual angle.

The Familiar-Size Cue

Size and distance go together inseparably and are two aspects of a more fundamental, unitary perceptual activity: the appreciation of spatial extent. The strong relationship between size and distance judgments causes errors in size perception to lead to errors in distance perceptions and vice versa. In simulations of fixed-wing aircraft this has not become a problem because of the lack of maneuvers requiring continuous *precise* size and distance judgments.

Size constancy does not work unless we have some knowledge of the objects being perceived, some knowledge and expectations about their usual, familiar size, and some knowledge about their distance from us. For instance, a large, unfamiliar spherical object viewed on a runway from 5,000 feet can easily be localized in distance so that its size can be known. However, if the same unfamiliar sphere is seen at some distance in a clear blue sky, neither its size nor its distance can be known. If both size and distance are unknown, then it is easy for illusions and perceptual errors to occur, since one cannot prevent oneself from forming a percept and a judgment, even though erroneous, about the size and distance of the unfamiliar object.

The perceptions referred to are not about naming size and distance in terms of a metric like feet or meters. People are very poor at that task. It is about operational action judgments like, "Can I land in that distance?" "Can I clear that obstacle?" "How long will it take me to get there?" Trained people are usually very good at making these kinds of judgments. A vivid illustration of the interdependency of size and distance is provided by Emmert's law for after-images. An after-image subtends a

constant retinal size and usually is of unfamiliar size. When the gaze is shifted outward and the after-image is localized on increasingly distant surfaces it is perceived as growing larger as a function of distance. Its size is thus completely determined by distance when its retinal image size is constant.

If instead of a nebulous sphere it is a Cessna 172 that is seen at a distance in a featureless sky, there is no problem in estimating its distance as a function of its known size, not at least to an accuracy sufficient for making operational decisions. Unfortunately, the computer-generated depictions of objects that are familiar in aviation operations frequently do not have the compelling realness of actual objects, so do not have familiar size value. This lack is made even worse by the fact that, as discussed above, the abstract objects grow without perceptual restraint as they "approach" the viewer.

Texture

There is a stable relationship between familiar-size and the functional utility of ground texture in visual scenes. Texture provides several kinds of information: it provides a ground plane and defines a surface when it is used for, say, tire marks on runways; it provides cues to horizontal extent as its gradient tightens with distance; and it provides cues to vertical distance as its elements are seen to separate and individuate as the ground plane is approached. The first two of these, surface texture and gradient, provide cues that need no intermediation; they communicate directly. The third, individuation of texture elements, provides information about the direction of altitude change but very little about the precise extent unless the elements are well-known, familiar objects, for example, sheep, a field of cabbages, a crowd of people. In the real world, as discussed, the perceived sizes of such objects are good cues to their distance from an observer. In simulators, the difficulties mentioned above with size distortion mitigate their value, for they do not retain size constancy. They become size-indeterminate at close ranges. And again, with computer-generated objects, there is frequently no information relating to familiar size. The objects are not of phenomenal size but are geometrical caricatures of real objects; as a result, they cannot be used as precision cues because they do not contain that inherent information.

An observer in a military helicopter simulator noticed that one large part of the gaming ground-plane was devoted to repeated, computer-generated images of abstract objects, each of which appeared to be a system of spirals or swirls of interwoven leaves. From one distance they could easily be taken to be a field of cabbages. They seemed to have the first two characteristics of texture — ground-plane localization and gradient. However, as altitude decreased, the textural effect began to be lost and they became individuated, separated objects. They became more meaningless and grew not only in visual angle as they should, but also in *perceived* size, a result of the breakdown of size constancy in these visual scenes. So the third characteristic of texture, that is, perceived distance, as derived from the familiar size of texture elements, was not effective.

BUT THE EAGLE AND HUMMINGBIRD ARE DIFFERENT

As mentioned, these departures from strict optical-visual fidelity have not been significant factors in the use of fixed-wing aircraft simulators. The sweeping validation

of fixed-wing simulators, as substitutes for aircraft in training, as covered under the three phases of the Federal Aviation Administration's (FAA's) Advanced Simulation Plan (Title 14, Part 121, Appendix H), seems to have been well-advised. It has been in effect for more than a decade in spite of the lack of visual fidelity in the simulated visual scene. At least in the fixed-wing simulators, even though the desideratum of *perceptual fidelity* is violated, their *functional fidelity* seems to be adequate to the task of training and qualifying large numbers of professional pilots in a much more efficient, safe, and economical way than can be accomplished in the aircraft.

But there are differences between the maneuvers conducted in fixed-wing and rotary-wing aircraft, differences that are analogous to the differences between the flight repertoires of the eagle and the hummingbird. As has been mentioned, the flight of the eagle must be, like the fixed-wing aircraft, forward-oriented. For fixed-wing aircraft, with their ever-forward velocity vector, the only times that a ground-plane orientation is critical is on takeoff and in the flare and landing. Even then, however, in both the aircraft and simulator, visual attention is directed forward, not downward. One's orientation to the ground and departure and return to it are determined from the orientation of one's ego-center, the ground plane, and its extension to the horizon.

Not so the hummingbird and rotary-wing aircraft. They are omni-translatable. Like rotorcraft, the hummingbird creates lift locally and routinely does bob-ups, bob-downs, sidesteps, pirouettes, and dolphins, and can translate sideward, forward, backward, up, and down, and can do combinations of these. So it is that the rotary-wing pilot, who also does these maneuvers while surrounded by several tons of technology, has an intense interest in his vertical orientation with respect to a ground plane. Also, he has more than just a passing interest in being able to judge vertical distances and rates, and to be continuously able to gauge within a few feet the distance of his ego-center from the firm plane beneath his aircraft. Unlike the fixed-wing pilot trainee, he needs a simulated ground plane that is located downward not forward, as well as valid visual cues with respect to it. None of these is adequately represented in current simulator visual scenes. It is always necessary to imagine the ground plane by extrapolating from the forward-oriented, two-dimensional representation of three-dimensional space; the third coordinate axis is imaginary and its absence constitutes a gaping inadequacy in perceptual fidelity.

Current simulator visual-scene technology has some serious limitations when applied to the training of rotary-wing pilots in the many near-the-ground operational maneuvers they routinely perform in the national airspace system. The visual scene does not fully support the training and therefore has dubious functional fidelity. As has been discussed, there are two general weaknesses in visual-scene technology when applied to vertical flight simulators, neither of which causes significant problems in fixed-wing simulators, at least not for civil fixed-wing training, which is our current concern. These were seen to be (1) the nullification of three major visual functions in collimated systems: stereopsis, vergence, and accommodation, together with their perceptual consequences; and (2) the attempt to adapt the forward-oriented visual scenes of fixed-wing simulators to the downward-oriented world of rotary-wing operations.

There are ways to counter these two anomalies, but they involve departures from strict physical fidelity in the interest of optimizing training fidelity. They will be resisted by proponents of maximum fidelity and, thereby, maximum cost. The first

involves the use of an uncollimated projection technique that moves closer to perceptual fidelity and obviates perceptual irrealism. The second involves the use of a local ground-plane projection so that extrapolation from a forward-oriented ground plane to the ego-centered ground plane is not the only way to deal with maneuvers in the local vertical. This latter would result in a simulator cab configuration that would depart from strict physical fidelity. But if its use results in the obviation of complaints about the inability in the simulator to estimate visual extents and rates in low-speed, low-altitude flight, then the training could well be more realistic and efficient, even though some fidelity has been compromised. The industry is invited to investigate the transfer of training resulting from such strategies before hardening subsequent simulator configurations.

THE DYNAMIC CUE: MOTION PERSPECTIVE

To this point we have referred to several of the visual depth-perception processes and cues that are well known to behavioral and visual scientists. However, these disciplines have very little to say about the mechanisms and operation of vision in three-dimensional, dynamically changing, real-world tasks like those occurring in high-performance aircraft in low-level flight over unfamiliar terrain. The visual localization of one's self (vehicle) in such contexts and the perception of the rate and direction of change of that locus may only be secondarily dependent on the operation of the conventionally accepted cues discussed above. It is possible that these visual perceptions result from a very complex process involving the integration of the apparent relative motion of many proximal terrain and cultural features.

Analysis

The first thorough description of motion-perspective cues to distance was provided by Helmholtz (ref. 4), as cited by Harker and Jones (ref. 5). Although the subject has been extensively studied by Gibson et al. (ref. 6), and by others, it has remained an odd sort of mechanism thought to provide some cues to relative depth. The mechanism has been associated with other terms, for example, optic flow, streaming, monocular movement parallax, and shear and motion parallax. All relate to the basic idea that any visual field contains movement patterns dictated by the relative motion between an observer and the outside world.

Briefly stated, if relative motion can be characterized by two quantities, that is, by translational and rotational motion vectors that are defined relative to coordinates in the outside world, then the appearance of the outside world during such movements takes on definite patterns. For pure translational movement toward an impact point, all objects in the visual field will stream outward from that point. For a pure rotation, however, the pattern is circular, arching around the point corresponding to the axis of rotation. As we move through the fixed outside world, the vector combination of these two patterns is impressed on the retinas of our eyes.

It is suspected that these patterns are learned and used by the human infant following its first attempts at hand, head, and eye coordination, and that the reflex is further refined by the time the infant is crawling and walking. It is probably very well

developed in the young child, permitting it to move gracefully and perform amazing feats of balance and locomotion.

For persons who drive automobiles and fly aircraft, the subliminal integration of the movement patterns of many objects in the visual field into the visual cues of angular and translational velocity is probably highly developed.

The integration of these patterns does not appear to depend on the gaze-point relative to the direction of movement or rotation; however, it could be expected that the streaming patterns corresponding to translational movement are probably most accurately interpreted by the visual sense when the gaze-point is near (within 90° of) the impact point or direction of translation.

The mathematical expression for the absolute angular velocity of any object in the visual field is given below:

Angular movement:

$$\omega_p = -\Omega \sin P \quad (1)$$

Translational movement:

$$\omega_T = (V \sin \theta) / R \quad (2)$$

where

ω_p = apparent angular velocity of an object in the visual field due to observer rotation, rad/sec

Ω = observer angular velocity, rad/sec

P = angle between the direction of rotation and the direction to the object

ω_T = apparent angular velocity of an object in the visual field due to observer translation, rad/sec

V = observer translational velocity, ft/sec

θ = angle between direction of translational movement and direction to the object

R = distance from observer to object, ft

The idea of motion perspective is that many objects in the visual field will be sampled and that the impressions will be integrated into the perception of observer angular velocity and distance to the object. The observer angular velocity perception process is straightforward, and is demonstrated by rewriting equation (1) thus:

$$\Omega = -\omega_p / \sin P \quad (3)$$

The observer's angular velocity is simply the apparent angular velocity of an object divided by the sine of the angle between the direction of rotation and the direction to the object. The perception of the angle P requires the sampling of several objects that are not near the axis of rotation, so that the angle P of each may be determined.

The corresponding situation for translational movement requires some interpretation. In this case, a similar rewriting of equation (2) results in the following:

$$R/V = \sin \theta / \omega_T \quad (4)$$

The first interpretation can be seen by dividing R and V by D , a characteristic dimension of the rotary-wing aircraft such as the diameter of the rotor. The new equation would be

$$R/D = (V/D) \sin \theta / \omega_T \quad (5)$$

The formula implies that if the rotorcraft's velocity were known in terms of rotor diameters per second (V/D), then the distance to the object could be inferred (in terms of rotor diameters) if the angular velocity of the object was observed and a sufficient number of object angular velocities were sampled in order to perceive the angle θ to each. Several objects must be sampled in order to determine the observer's aim point, so that the angle θ may be determined from this point to each object.

The second interpretation requires no knowledge of flight speed in terms of a characteristic dimension D , but rather yields a direct perception of distance to the object in terms of time to impact (assuming the observer was traveling straight toward it). This may be seen by considering the left side of equation (4) to be the time-to-impact, namely R/V directly. This means that a depth map may be directly perceived in terms of the time-to-impact of each object in the visual field by sampling the angular velocity of each object and the pattern of movement for several objects in order to perceive the angle θ to each.

The mathematics suggest that a minimum number of objects must be simultaneously seen in the visual field for the mechanism to work. Zacharias provided a vigorous mathematical treatment of the general equations in vector form, and has concluded that a minimum of *three* objects is required in order to make the number of equations equal to the number of unknowns, thereby yielding a solution for the impact time-depth map for those three objects, considering translation only (ref. 7).

To illustrate the use of the motion perspective mechanism in a perceptual process, the following example is offered. Consider a rotary-wing pilot as he approaches a hill. For the sake of simplicity, let us make the hill a two-dimensional one, similar to one cycle in a corrugated roof. Let us assume that two points will be placed on the surface, one above the impact point, and one below it as shown in figure 1.

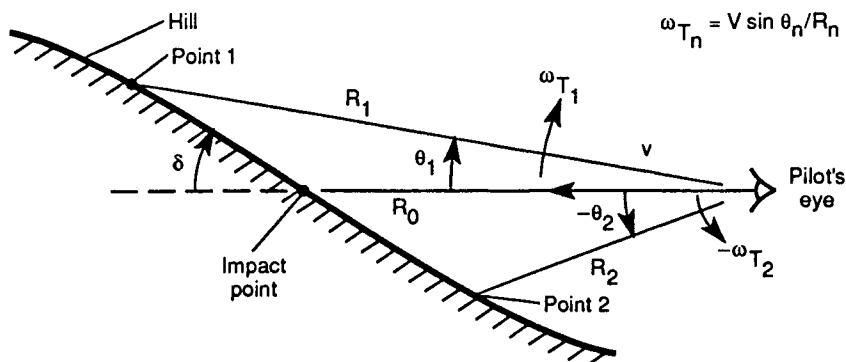


Figure 1. Motion perspective parameter for the approach to an inclined plane.

The apparent angular velocity of each point is given by the following equation:

$$\omega_{Tn} = \left(\frac{V}{R_0} \right) \frac{\sin \theta_n \sin (\delta - \theta_n)}{\sin \delta} \quad (6)$$

where

θ_n = elevation angle of the point n

δ = slope angle of the plane containing points 1 and 2

V = rotorcraft velocity, ft/sec

R_0 = horizontal distance to slope, ft

Rewriting equation (6) for the time-to-impact TI gives the following:

$$TI = \frac{R_0}{V} = \frac{\sin \theta_1 \sin (\delta - \theta_1)}{\omega_{T1} \sin \delta} = \frac{\sin \theta_2 \sin (\delta - \theta_2)}{\omega_{T2} \sin \delta} \quad (7)$$

Equation (7) is the key to the interpretation of the time-to-impact depth map, since if TI can be determined for the impact point, the time-to-impact for any other point can be computed by the relation:

$$\frac{R_n}{R_0} = \frac{\sin \delta}{\sin (\delta - \theta_n)} \quad (8)$$

The solution of equation (7) is straightforward. First, two points are required, as a minimum, so that an equation for the slope angle can be formed from the two right components of equation (7), namely,

$$\frac{\sin(\delta - \theta_1)}{\sin(\delta - \theta_2)} = \frac{\omega_{T_1}}{\omega_{T_2}} \frac{\sin \theta_2}{\sin \theta_1} \quad (9)$$

Equation (9) is solved for δ following the observation of the angular velocities ω_{T_1} and ω_{T_2} , and the angles θ_1 and θ_2 ; the result is then used in equation (7) to compute the impact time T .

If a third point is used, it will be obvious that it should be possible to define the time-to-impact depth map for a plane formed by those three points. Hence the conclusion that mathematically speaking, only three points are required to effect the perception of observer orientation relative to the plane and time-to-impact to the three points, and, for that matter, to any point in the plane, including the actual impact point.

Some preliminary calculations were performed to determine the accuracy of the time-to-impact and slope-angle estimates, assuming errors in the perception of the angular velocities ω_{T_1} and ω_{T_2} , and their corresponding elevation angles θ_1 and θ_2 (relative to the impact point). A true slope of 32° and a time-to-impact of 4 sec were chosen for the calculations. The corresponding true angular velocities for two points, one at $\theta_1 = -10^\circ$ and the second at $\theta_2 = -40^\circ$, were also calculated.

The assumption was then made that the perceived angles (absolute value) were too high by 5%, and that the perceived angular velocities (absolute values) were too low by 10%, yielding a worst-case based on the minimum number of points and reasonable threshold errors. The results showed a perceived slope angle of 31.5° , and a perceived time-to-impact of 4.73 sec, approximately in error by -1.6% and 18.3% , respectively.

It would be logical to expect that the use of more points could only improve the accuracy in a way similar to the improvement in a celestial navigational fix when more sightings are taken. In the motion perspective case, the perceptual thresholds would be distributed about a mean of zero, thereby making the distribution of impact times also cluster about the true value. The use of many points, therefore, simply averages out the error! Consider that the human eye has thousands of receptors to apply to the sampling of perhaps hundreds, even thousands of objects in the visual field. Perhaps one of the functions of the many photoreceptors in the parafovea of the eye is the sampling of object stimuli in order to allow the accurate perception of movement by using averaged perceptions based on the motion perspective mechanism.

Further thoughts on the subject of motion perspective have been developed based on observations of scenes produced by computer-image generators at the U.S. Air Force Aerospace Medical Research and Human Resources Laboratories and at the Evans and Sutherland Computer Corp., and by personal communications with Dr. Greg L. Zacharias of Charles River Analytics, Inc.

These thoughts are partly the result of research funded by the Air Force in an effort to model visual- and motion-cue effects on pilot performance. Since the detailed findings of that effort will include a rigorous analysis of motion perspective, only the findings important to the present work will be highlighted.

First, on the analytical side, Zacharias has analyzed the motion-perspective mechanism applied to a randomly distributed texture field on a flat surface, and has found that the theoretical minimum number of texture elements required for the perception of self-motion is three for translational motion only, and five for a combination of translational and rotational motion. His analysis included imperfect (noisy) perceptions of the angular velocity of texture elements, and consequently demonstrated that the error in the perception of aim point (impact point) decreased with an increasing number of texture elements. From the convergence properties of the computer solution, he also infers that the number of points must be greater than the theoretical minimum in order to obtain a solution for the estimated aim point, a typical value being 20 or more texture elements.

Secondly, on the experimental side, insights into the question of how many texture elements are required were gained by observing electronically generated pictures of surfaces containing arrays of texture elements or points. The eyepoint corresponding to these pictures was moved through or over the texture field in order to see if the shape of the underlying supporting surface could be perceived. The surface shapes more commonly investigated were flat and were inclined in the direction of translational movement or were sections of two-dimensional sinusoids similar to a piece of corrugated roof. The conclusion is that, for a given density of random texture, a certain amount of time was required to perceive surface shape. Zacharias stated it another way by saying, "It is like solving the sampling theorem in three dimensions." Although the nature of the complex interactions between estimated surface shape and observer velocity, time allotted for perception, surface shape, and surface decoration (texture density) is the subject of the Air Force work, a preliminary best estimate based on the observations is a mean texture spacing of one eye-height for a randomly distributed array on a nearly flat surface.

One more point should be made about the perception of a translational flow field under conditions of high-rate rotations. The streaming translational flow field seemed to disappear during high-rate rolls, suggesting that a relatively stable retinal image is required to perceive the impact time-depth map and aim-point information contained in a translational visual field.

In summary, the following conclusions may be stated:

1. Natural terrain contains few, if any, stimuli that could be integrated into visual cues of absolute size. Those that are present require specialized knowledge of the distribution of size, shape, and appearance of vegetation, or of the dynamic nature of falling water, vegetation, smoke, or fire.
2. Because pilots are able to fly rotary-wing and fixed-wing aircraft at low altitudes over natural terrain devoid of cultural features, it is concluded that upon first encounter, the primary perceptual strategy in such areas is the use of motion perspective.

With repeated exposure to the area, the appearance of consistently encountered objects such as trees and shrubs is "calibrated" by the pilot so that faster, more accurate judgments of distance, based on the apparent/familiar-size mechanism, may be made to supplement the motion-perspective cues. If available, the stimuli for other mechanisms, such as aerial perspective and shading, may be used.

Perceptual Strategy

For low-level flight operations over natural terrain devoid of cultural features, the primary initial perceptual mechanism used is motion perspective. This is supplemented by other relative-size mechanisms, such as aerial and linear perspective, absolute size, and, apparent/familiar-size, through a "calibration" process akin to acquiring "air sense" knowledge of the specific terrain.

The motion perspective mechanism used may be interpreted in two ways. In the first, the observance of the absolute angular velocity of several objects and their positions relative to the impact point permits the pilot to perceive a "time-to-impact" depth map of the visual field. In the second interpretation, the pilot uses the same observations, but from a knowledge of his velocity in terms of some relevant vehicle dimension per second; he perceives a depth map in terms of this dimension. For rotary-wing aircraft, the velocity could be sensed in terms of rotor diameters per second, and the perception of depth in terms of rotor diameters.

Integration of Perceptual Strategy and Performance Envelope

The pilot constantly reconciles his knowledge of "where he can go" with his perceptions of "where he is going" and "what is out there" to achieve the desired clearances and speeds, while allowing himself some margins for safety. This means that he will superimpose a mental image of the current performance envelope onto his perception of the terrain shape ahead, and adjust the controls so as to place his future trajectory in places affording him desired clearances, masking, and adequate safety margins. The performance envelope must never be completely "filled with terrain," for this means imminent impact; however, to achieve close clearances, the envelope must be nearly filled. Since the regions of intense interest are the envelope and impact regions, the corresponding eye fixations are concentrated in these regions where foveal vision is used to search for identifiable objects and for optimum places to go, and where peripheral vision complements foveal vision to mediate the perception of surface shape and impact times. The corresponding eye-movement activity is concentrated in the vehicle impact field and surrounding envelope field, which are dictated by a knowledge of the performance capabilities of the pilot and vehicle.

The relationships among workload, clearances, and speed should be affected by the nature of the terrain being flown over. Generally, there is a direct relation between clearances and speed, a lower speed being associated with smaller clearances. The associated workload, however, may vary with both speed and clearances. It should also depend on the complexity of the terrain, a hilly terrain being more difficult to fly over than a flat one. The nature and number of the features that lie on the surface also should cause the workload to vary. Areas with sparse, low vegetation seen under low, diffuse illumination should demand high visual workload, possibly even staring. Areas

with many taller, more differentiated features, such as loosely spaced trees under direct illumination with shading effects, should be easier, since surface-shape perceptions should be possible in shorter times. Finally, areas with cultural features that can be readily recognized or identified should reduce workload still further.

IMPLICATIONS FOR IMAGERY DESIGN

Philosophy

Because it is imperative that the visual cues presented to the pilot, as well as his associated workload in a near-Earth simulator, be similar to those in the real world, the simulated scenes require that the visual scan pattern (gaze-point distribution and dwell times) and perceptual strategy also be similar.

A case was made earlier, based on flight dynamic concepts, that the pilot's gaze-points are distributed mostly in the immediate impact field from 3 to 5 sec ahead, with nearly all the remaining fixations contained in the surrounding envelope field. This field is composed of azimuth angles of approximately $\pm 60^\circ$, and elevation angles of $\pm 30^\circ$.

Furthermore, a case was also made, based on a review of perceptual mechanisms and a survey of some terrain samples, that the only reliable, that is, always available, mechanism useful to the pilot for perceiving terrain shape and depth is motion perspective. This is because the terrain most likely to be overflown during near-Earth flight is natural, that is, it appears as randomly distributed incoherent patches of light attached to Earth's surface with weak texture gradients. This kind of terrain, therefore, offers few, if any, means of establishing distances by the observation of familiar objects, and only sporadic opportunities to use other mechanisms such as aerial and linear perspective, shading, and interposition.

A Case for Texture

If imagery for near-Earth flight simulation were composed only of texture elements randomly distributed on the terrain surface, the necessary perceptions of terrain shape and depth would be made using motion perspective. This will work even if the distribution of texture-element size on the surface is so great that no obvious texture gradients are visible during static viewing. There are areas of Earth's surface that have this appearance; for example, highly eroded canyons containing mostly bare rock formations and individual rocks of many sizes and shapes. Each rock is visible, depending on distance and illumination, but because they vary so widely in size, shape, and color, they are unidentifiable and called "trash" by some pilots. Distances to unidentifiable features are extremely difficult to judge under static conditions, but while moving, the observer can ascertain the underlying terrain shape and distance to each feature using motion perspective, as long as enough of them are visible. The question of "how much is enough" is, of course, the main question here.

A limited number of "observational tests" performed using various computer-generated scenes has revealed a rough rule of thumb. This rule states that in order for

terrain shape and depth to be perceivable in a few seconds or less, *the mean spacing of texture elements decorating the terrain should be one eye-height or less* (the distance between the pilot's eye and a point on the terrain surface or feature directly below). This value of texture density has been found to be adequate in facilitating the perception of terrain shape under dynamic conditions. The reader is cautioned that this estimate is preliminary. The problem is complex, for the elements include the dynamic perception of terrain shape given a density of texture decoration, the surface itself, and the observer's motion. There is considerable room for improvement of this estimate, and some suggestions of how to do this are described below.

Suggested Imagery Details

In areas to be overflown, a texture decoration with a mean texture element spacing of one eye-height is deemed a minimum texture level needed to reveal surface shape using motion perspective. This means that a spacing of 5 feet is adequate for areas where hovering operations, including landing, are to take place. Over other areas where higher-speed nap-of-the-Earth (NOE) flight is conducted, a spacing of 15-20 feet should be adequate. The texture may be composed of irregularly shaped polygons in the surface of the terrain. The array size should appear random, as does natural texture in the real world. This may be accomplished by using five different sizes of polygons where the ratio of the largest to the smallest is about 10 to 1. (The size of a polygon is defined as the diameter of a circle having the same area.) Such an array of texture elements should begin to show texture gradients for distances greater than 10 eye-heights.

The surfaces decorated as suggested above should be the most difficult to fly over at altitudes above ground level (AGL) of one mean texture element spacing or less. This is because considerable attention must be paid to the streaming texture pattern in order to perceive the surface shape ahead. The gaze can be expected to be drawn to objects near the impact point or aim point, and dwell times may be long, that is, 0.5 - 2 sec. An amount of texture less than that suggested above should result in increasing the workload and reducing height-holding performance to such an extent that an impact is certain.

To make the areas easier to fly over, one would think that more texture elements are needed. This is probably false, however, and the addition of more texture elements should not significantly reduce workload or improve height-holding performance. What should reduce workload or improve performance or both is the addition of coherent objects that more easily facilitate a static perception of terrain surface shape and observer position relative to that surface.

The addition of vertical objects should also reduce workload or improve height-holding performance or both. Vertical objects such as poles or renditions of trees (tetrahedrons, triangles, etc.) permit a static perception of height relative to the object height and orientation under the assumption that the object is vertical. The perceptual mechanism was pointed out by Harker and Jones (ref. 5). The observer's eye-height relative to the height of the vertical object is simply the ratio of the vertical angle formed by the horizon and the bottom of the object to the angle subtended by the object itself (valid only for a flat Earth). In order to fly just at tree-top level, one only has to fly so as to maintain the tree tops silhouetted against the horizon. The perception

is relatively easy to make, but becomes increasingly inaccurate when the horizon line position is occluded by nearby hills or trees, and consequently has to be estimated by means other than direct viewing.

It should be remembered, however, that trees vary in height and shape so that the tree renditions should also vary in height and shape. This simply means that the use of closely spaced trees distributed in height will induce pilots to fly near the surface formed by the tree tops, which forms a convenient and soft Earth reference. When trees are widely spaced so that a rotary-wing aircraft can pass between them, the eye-height is probably perceived using the angle subtenses previously cited, and the spacing between trees, by the use of motion perspective. It is also obvious that actual trees do not offer cues to relative azimuth (bearing) owing to the random appearance of their crowns. Their "transparency," that is, the fact that the crown is not a solid mass but rather a complex array of leaves and branches, permits the detection of relative movement when viewing trees aligned in depth against a bright background.

The use of trees and other vertical objects should either ease the workload required to fly close to the ground or improve height-holding performance. The objects need not show changes with relative bearing, and should be distributed in size and shape so that static perceptions of absolute size are difficult. As an example, a survey of a stand of oak trees containing 26 specimens revealed variations in height from 4-80 feet and in maximum crown width from 4-56 feet.

It is tempting to suggest that trees be distributed similarly to texture, but trees are not uniformly distributed in nature. Since it is desirable, from an image-generation viewpoint, to use the minimum number of features, the trees should be sparse, as they are in semiarid regions. This means that they should be distributed mostly in gullies and valley floors with a few on ridge tops to help facilitate ridge crossings. Also, it is not necessary that they be three-dimensional or that they can be seen through.

Although an estimate was made of the mean spacing of texture elements, at this time it is not possible to determine an equivalent number for vertical objects such as trees. A suggested starting point for tree density is a value that results in a mean spacing of from 3-5 eye-heights for vertical objects whose average heights are equal to an eye-height.

As a final note, although highly coherent texture, such as a checkerboard pattern, should ease workload or improve height-holding performance or both, the use of such features is not recommended. They permit the use of linear perspective and apparent/familiar-size mechanisms in perceiving terrain shape — which is akin to the cues furnished by runways, orchards, row crops, and vineyards — and as a result, provide too many cues.

CONCLUSION

We chose to discuss visual-scene requirements in terms of two natural visual processes, that is, the near-Earth functional requirements in size and distance judgments and dynamic orientation and progress with respect to its surface. They were selected for their relevance to the task of maintaining orientation and control in vertical flight and were meant only to be illustrative of analyzing current simulator visual scene

technology for application to rotary-wing training. It was seen that there are inherent inadequacies in the current optical representation of the real visual world in fixed-wing simulators, inadequacies that may herald problems for vertical-flight training. An analysis was presented of the dynamic visual cues used by pilots in low-altitude flight over unfamiliar terrain, and some suggestions were made for the design of terrain textural elements that could provide or enhance these cues. It is hoped that the appeal to functional requirements used herein will generate further analysis by the industry to better define the more fundamental fidelity requirements in visual simulation. There are extant several comprehensive and encyclopedic treatments of the vast and complex area of simulation of the visual environment, but these are catalogs of elements rather than analyses of functional relationships. It must be noted that there has been no thoroughgoing examination of visual cues and dynamics.

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DEFINITIONS OF TERMS AND ABBREVIATIONS

AAFQE Army Air Forces Qualifying Examination
ab initio training beginning, basic flight training
AC Advisory Circular (FAA)
ACB Aircrew Classification Battery
accommodation change in visual focus in living optical systems
ACE Aircrew Coordination Evaluation [checklist]
AC 120-63 FAA Advisory Circular which will constitute standard for use in rotary-wing applications
Ada a computer software language
AFAST Alternate Flight Aptitude Selection Test
AFB Air Force Base
AFHRL Air Force Human Factors Resources Laboratory
AGL above ground level
AH-1FWS (AH-1 Cobra) Flight and Weapons Simulator
AHT Automated Hover Trainer (Army)
AI artificial intelligence
AIAA American Institute of Aeronautics and Astronautics
AIT air-intercept trainer — device used to train fighter pilots in use of stick controls for weapons and radar
AL Armstrong Laboratory (Air Force)
AO Area of Operations (Army)
AQC Aviator Qualification Course (Army)
AQP Advanced Qualification Program (FAA)
ARI Army Research Institute (U.S.)
ARIARDA Army Research Institute Aviation Research and Development Activity
ARINC Aeronautica Radio, Inc.; U. S. company whose electronic box sizes are international standards
ARPA Advanced Research Projects Agency
ASVAB Armed Services Vocational Aptitude Battery
ATC air-traffic control
ATG Approval Test Guide — documentation of simulator manufacturer's verification that a simulator's performance matches that of the aircraft it simulates, under similar conditions
ATHS Airborne target handoff system
ATOI Air Transportation Operations Inspector
ATM Aircrew Training Manual (Army)
autorotation rotation of a stalled symmetrical airfoil (as helicopter rotor blades following engine failure)

BAT Basic Attributes Test (Air Force)
BFITS basic flight instruction tutoring system

BGSU Bowling Green State University

BITE built-in test equipment

blade-element model rotor modeling technique in which each blade is treated as having a number of spanwise components and in which the equations of motion are solved at each one in real time at a number of azimuth positions using a relatively high iteration rate

budget constraint line a line representing a combination of inputs that results in a constant cost (as in training effectiveness evaluations)

C a computer software language

CAA Civil Aeronautics Administration (succeeded by Civil Aeronautics Board, in turn succeeded by FAA); Civil Aviation Authority (U.K.)

CAI computer-assisted instruction

CBFS computer-based flight simulation

CBT computer-based training

CCAB Complex Cognitive Assessment Battery

CEA cost-effectiveness analysis

CFR Code of Federal Regulations — codification of the general and permanent rules published in the Federal Register

c.g. center of gravity

CIFER Comprehensive Identification from Frequency Response — software package used with frequency-domain modeling techniques

CIG computer image generation

CMAQ Cockpit Management Attitudes Questionnaire

CRM cockpit-resource management — emphasis on crew's handling of communications, flight strategy, crew coordination, task sharing, decision making, and small-group problem solving

CTEA cost- and training-effectiveness analysis

CTER cumulative transfer effectiveness ratio

DA Department of the Army

DARPA Defense Advanced Research Projects Agency

DASE digital automatic stabilization equipment

DCSOPS Deputy Chief of Staff for Operations

DES Directorate of Evaluation and Standardization (Army)

DOD Department of Defense

DOF degree of freedom

DRC Dynamics Research Corporation

dynamic fidelity a measure of the preciseness with which simulator responses to input changes correspond to those of the simulated equipment when subjected to the same input changes

EBAT experimental BAT

engineering fidelity the preciseness with which a simulator physically duplicates the equipment it simulates

ETL effective translational lift

ETM emergency touchdown maneuver

FAA Federal Aviation Administration

FAR Federal Aviation Regulation

FAST Flight Aptitude Selection Test

fixed-wing aircraft conventional aircraft on which the wings are stationary; distinguished from rotary-wing aircraft on which lift is developed by assemblies of rotating airfoils (blades)

flight freeze simulator capability that allows the instructor to stop the training flight and then resume it at will from that point (as in explaining an important point or correcting a student's actions)

FLIR forward-looking infrared

FOHMD fiber-optic helmet-mounted display

FOJT formal on-the-job training

FORTRAN a computer software language

FSI FlightSafety International

FTD flight-training device

FTG Flight Training Guide

functional fidelity herein the degree of correspondence between the behaviors and skills practiced and learned in a training device and those required for criterion-referenced performance in the operational system

f/w fixed wing [aircraft]

glass cockpit cockpit in which conventional flight instruments are replaced by sophisticated digital electronic displays and interfaces

GT General Technical [test]

guidance and control one of three major human performance domains on the flight deck; the others are system management and flight management

HAI Helicopter Association International

Hertz unit of frequency of cyclic function, i.e., cycle per second

HMD helmet-mounted display

Hz Hertz, q.v.

IERW Initial Entry Rotary Wing [flight training course, Ft. Rucker]

IFR instrument flight rules

IFT intelligent flight trainer

IG image generator

IGE in ground effect

IMC instrument meteorological conditions

IP instructor pilot

IPISD Interservice Procedures for Instructional Systems Development

IRR Individual Ready Reserve (Army aviator program)

ISD instructional system development

ISS installation support school
ITER incremental transfer effectiveness ratio
ITF incremental transfer function
ITR iterations transfer ratio
ITS intelligent tutoring system

JPA job performance aid
JPM job performance measure

LOD level of detail
LOE line-oriented evaluation
LOFT line-oriented flight training
LRU line replaceable unit

mathematical model in simulation, the description and specification of the simulated aircraft's dynamic behavior, which comprises the various motions of the airframe and the states and performances of the various subsystems

METL Mission Essential Task List
MFD multifunction display
MILPERCEN Military Personnel Center
MPS Mission Proficiency Scale
MTT multi-task trainer

NAMRL Naval Aerospace Medicine Research Laboratory
NAS Naval Air Station
NASA National Aeronautics and Space Administration
NOE nap-of-the-Earth [flight near the surface]
NTH new training helicopter

OCM optimal control model

PC personal computer
perceptual fidelity herein the degree of correspondence between the trainees' perceptual experiences in a training device and those experienced in the operational system
PIC pilot in command
PIO pilot-induced oscillation
POI principal operations inspector
product isoquants contours of equal performance across a range of interest for given training factors, i.e., combinations of training factors that result in equal performance
PSSTG Pilot Selection Special Topic Group

RFAST Revised Flight Aptitude Selection Test
RISC reduced instruction set computing
rotary-wing aircraft general term used herein to include helicopters and tilt-rotor and tilt-wing aircraft

c-4.

- rotor-disk model** rotor modeling technique based on an analysis of rotor behavior in which segments of the blade are considered as finite elements but then proceeds to solve the equations generally as a disk
- RS** resident school (flight training)
- r/w** rotary wing
- seat-mile cost** conventional cost number reflecting the total cost of moving each seat of an aircraft 1 mile
- SIC** second in command
- simulator** equipment, usually computer-driven, that simulates a given system and that responds accordingly to applied input changes
- simulator fidelity** See engineering fidelity; dynamic fidelity; functional fidelity
- SIP** standardization instructor pilot
- size constancy** the tendency in human visual perception for objects to retain their familiar size when their visual angle changes
- sling load** load suspended from a helicopter (as in installing or removing heavy equipment from sites difficult to access)
- SME** subject matter expert
- SP** student pilot
- SR** substitution ratio
- STEP** self-teaching exportable package
- stereopsis** in binocular vision the perception of objects as three dimensional resulting from the neural integration (fusion) of the two disparate retinal images
- STRATA** Simulation Training Research Advanced Test-Bed for Aviation
- system management** one of the three major human performance domains on the flight deck, the others being guidance and control and flight management — the system management and flight management domains are considered to be the major sources of operational errors and accidents
- TAPSTEM** [Armed Services] Training and Personnel Systems Sciences and Technology Evaluation Management Committee
- TAWL** Task Analysis/Workload
- TER** transfer effectiveness ratio
- texture density** the average number of elements of a given size per unit area in an extended surface
- texture gradient** the apparent increase in texture density with distance of an extended surface
- tilt-rotor** a vertical takeoff and landing aircraft that relies on an assembly of rotating blades whose plane of rotation can be varied from horizontal (as a helicopter) to vertical (as conventional propellers)
- tilt-wing** a vertical takeoff and landing aircraft on which the wing can be rotated to change the plane of rotation of an assembly of rotating blades from the horizontal (helicopter mode) to the vertical (conventional aircraft mode)
- TOSS** TAWL Operator Simulation System
- TOT** transfer of training (e.g., from simulator to aircraft)
- TRADOC** Training and Doctrine Command
- TRP** Technology Reinvestment Project (ARPA)

UNIX computer operating system designed for use with microprocessors and with the C programming language

USAAVNC U.S. Army Aviation Center (Ft. Rucker)

vergence the visual/motor process of changing the divergence or convergence of the eyes in binocular vision

VFR visual flight rules

VMS Vertical Motion Simulator (facility at Ames Research Center, Moffett Field, Calif.)

VR virtual reality

WOC warrant officer candidate (Army trainee)

ZFT zero flight time (as in a proficiency check carried out exclusively in a simulator without use of the simulated aircraft)

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